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The Effect of MOPP4 on M198 Howitzer Crew Performance
Volume 1—Emplacement and Displacement Times and Rates of Fire

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13. ABSTRACT *(Maximum 200 words)*

This work represents field measurements of performance times for the crew of an M198 howitzer. The M198 is a towed, 155mm artillery piece, manned by a 10-member US Marine crew for this exercise. Baseline times in battle dress uniform and degraded times in full nuclear and chemical protective gear (MOPP4) are included. Reported times consist of emplacement time, displacement time, time to first round (TTFR), and time between rounds (TBR) for three fire mission types.

Baseline times for TTFR and TBR show a decrease (improvement) with repetition number during a day's fire missions, indicating a significant practice or warm-up effect. Times for TTFR and TBR show a significant increase (degradation) when the crew is at MOPP4. The performance degradation worsens with mission repetition (increasing time-in-MOPP4). These measurements are part of the ongoing effort of DNA's Radiation Risk/Safety program to support quantification of military performance degradation in an NBC environment.

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SUMMARY

This report, *The Effect of MOPP4 on M198 Howitzer Crew Performance,* presents field measurements of task completion times in Battle Dress Uniform (BDU) and Mission-Oriented Protective Posture, Level 4 (MOPP4) for the crew of a towed, 155 mm howitzer. This volume of the report, *Emplacement and Displacement Times and Rates of Fire,* covers task times for howitzer emplacement, howitzer displacement, time to first round, and time between rounds. Volume II, *Task Times for Fire Missions*, covers individual crewmember tasks.

Table S-1 summarizes results from this volume for howitzer emplacement and displacement activities, including a measure of performance defined as the ratio of the baseline task completion time in BDU to the task completion time in MOPP4. The performance ratio is 1.0 if the time in MOPP4 is the same as in BDU and degrades toward 0.0 as the task time in MOPP4 increases. The data in Table S-1 indicates minimal performance degradation within the first half hour of donning MOPP4 for the emplacement tasks of laying the howitzer and setting up ammo stacks. On the other hand, after 2 to 4 hours in MOPP4, there are statistically significant degradations of 30% to 40% for laying the howitzer, ammo set up, and howitzer displacement. Finally, for the relatively simple task of a short, straight-line drive to the firing point, there is no significant degradation during the first 3 hours in MOPP4.

Table S-1. Summary of baseline task completion times and performance in MOPP4 for howitzer emplacement/displacement activities.

Task	*BDU Baseline Task Time*	*Time in MOPP4*	*Performance Ratio in MOPP4*
Drive to Firing Point	38 ± 7 s	0 - 3 h	1.05 ± 0.23
Lay Howitzer	245 ± 13 s	0.1 h	0.97 ± 0.13
First Ammo Set Up, 30 Rds	1256 s	0.4 h	0.97 ± 0.06
Displacement for Resupply	544 ± 90 s	2.1 h	0.60 ± 0.11
Lay Howitzer	245 ± 13 s	3.4 h	0.70 ± 0.07
Second Ammo Set Up, 59 Rds	1450 s	3.6 h	0.56 ± 0.06

This volume analyzes three types of fire missions for time to first round (TTFR) and time between rounds (TBR). The bulk of the fire missions are *normal*, that is, they consist of 3 to 6 rounds on a single aim point with an elevation angle less than 1000 milliradians. The other two types are *high angle* (HA), consisting of 5 rounds on a single aim point with elevation angle 1000 milliradians or greater, and *zone and sweep* (ZS), consisting of 25 rounds on a 5 by 5 grid of aim points.

Baseline times for TTFR and TBR for normal fire missions in BDU show a small, statistically significant, daily practice or warmup effect. For example, regression analysis of TTFR versus repetition number aggregated over all crews shows that after 17 fire missions, TTFR improves from 52 to 42 seconds. This effect appears to be a warmup effect rather than a learning effect since it occurs even for Crew 1 for which the BDU data was taken on the third and last day of their participation in the exercise. On the other hand, for 5 out of 10 fire missions with crewmembers in MOPP4, regression analysis of TTFR or TBR versus time-in-MOPP4 shows statistically significant increases in task times. None of the cases show improvement in times, indicating that neither warmup nor learning effects in MOPP4 were dominant on an overall crew performance basis in this exercise. These observations show that performance of the M198 crews as measured by rates of fire clearly degrade with increasing time in MOPP4. The time dependence of performance degradation is analyzed further in Volume II of this report.

Table S-2 summarizes performance ratios in MOPP4 for TTFR and TBR for this exercise averaged without regard for time-in-MOPP4. Most of the data is for time-in-MOPP4 of 1 to 2 hours with some data in the 4 to 6 hour range. Ambient temperatures were mostly in the range of 75 to 85 degrees Fahrenheit and relative humidity mostly from 65% to 85%.

Table S-2. Summary of average performance ratios and standard errors for the M198 howitzer with crew in MOPP4 for rates of fire.

Fire mission type	*Time to first round Performance ratio*	*Time between rounds Performance ratio*
Normal	0.63 ± 0.03	0.61 ± 0.02
High angle	0.71 ± 0.07	0.72 ± 0.03
Zone & sweep	0.69 ± 0.06	0.52 ± 0.02

PREFACE

This report was prepared for the Radiation Risk/Safety Program at the U. S. Defense Nuclear Agency (DNA). DNA's technical monitors for this project were Mr. Robert A. Kehlet and Dr. Robert W. Young of the Environments and Modeling Division. Data collection and analysis were supported jointly by Horizons Technology, Inc. (HTI), Micro Analysis and Design, Inc. (MA&D), and ARES Corporation with funding from DNA through Contracts DNA 001-90-C-0118, DNA 001-90-C-0139, and DNA 001-90-C-0164, respectively. Pacific-Sierra Research Corporation (PSR) participated with funding from these same contracts through HTI, MA&D, and ARES subcontracts S-419-F-A1, SC 102, and ARES-PSR-90-C-001, respectively.

Data were collected by DNA researchers from ARES, EAI Corporation, and PSR on a noninterference basis during a four-week exercise conducted in August of 1992 by the U.S. Army Human Engineering Laboratory (HEL) at Aberdeen Proving Ground. The exercise, *Assessment of Towed Artillery (M198) Crew Performance in NBC Protective Clothing*, was directed by Mr. Orest Zubal of HEL whose cooperation is gratefully acknowledged. The exercise was funded by the P^2NBC^2 Project Office of the U. S. Army, the acronym standing for *Psychological and Physiological Effects of the NBC Environment and Sustained Operations on Systems in Combat.* Mr. Kehlet of DNA and Mr. Don Cunningham, P^2NBC^2 Program Manager, U. S. Army Chemical School, were instrumental in arranging on short notice for the DNA research team to take advantage of this important data collection opportunity.

Volume II of this report provides detailed analysis the MOPP4-induced performance degradation of individual tasks during fire missions. Volume III provides a comparison of field-measured, crewmember performance degradation with estimates of performance degradation obtained from the same crewmembers with a questionnaire.

CONVERSION TABLE

Conversion factors for U.S. customary to metric (SI) units of measurement

To Convert From	To	Multiply
angstrom	meters (m)	1.000 000 X E–10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E+2
bar	kilo pascal (kPa)	1.000 000 X E+2
barn	meter^2 (m^2)	1.000 000 X E–28
British Thermal unit (thermochemical)	joule (J)	1.054 350 X E+3
calorie (thermochemical)	joule (J)	4.184 000
cal (thermochemical)/cm^2	mega joule/m^2(MJ/m^2)	4.184 000 X E–2
curie	giga becquerel (GBq)*	3.700 000 X E+1
degree (angle)	radian (rad)	1.745 329 X E–2
degree Fahrenheit	degree kelvin (K)	$t_K=(t^\circ f + 459.67)/1.8$
electron volt	joule (J)	1.602 19 X E–19
erg	joule (J)	1.000 000 X E–7
erg/second	watt (W)	1.000 000 X E–7
foot	meter (m)	3.048 000 X E–1
foot–pound–force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E–3
inch	meter (m)	2.540 000 X E–2
jerk	joule (J)	1.000 000 X E+9
joule/kilogram (J/Kg) (radiation dose absorbed)	Gray (Gy)	1.000 000
kilotons	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E+3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E+3
ktap	newton–second/m^2 (N–s/m^2)	1.000 000 X E+2
micron	meter (m)	1.000 000 X E–6
mil	meter (m)	2.540 000 X E–5
mile (international)	meter (m)	1.609 344 X E+3
ounce	kilogram (kg)	2.834 952 X E–2
pound–force (lbf avoirdupois)	newton (N)	4.448 222
pound–force inch	newton–meter (N·m)	1.129 848 X E–1
pound–force/inch	newton/meter (N/m)	1.751 268 X E+2
pound–force/foot^2	kilo pascal (kPa)	4.788 026 X E–2
pound–force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound–mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E–1
pound–mass–foot^2 (moment of inertia)	kilogram–meter^2 (kg·m^2)	4.214 011 X E–2
pound–mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E+1
rad (radiation dose absorbed)	Gray (Gy)**	1.000 000 X E–2
roentgen	coulomb/kilogram (C/kg)	2.579 760 X E–4
shake	second (s)	1.000 000 X E–8
slug	kilogram (kg)	1.459 390 X E+1
torr (mm Hg. 0°C)	kilo pascal (kPa)	1.333 22 X E–1

*The becquerel (Bq) is the SI unit of radioactivity; Bp = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1
INTRODUCTION

During August of 1992, a team of contractors sponsored by the Defense Nuclear Agency (DNA) participated in an exercise at Aberdeen Proving Ground under the U. S. Army's P^2NBC^2 program. The purpose of the exercise was to measure the crew performance of an M198 howitzer for different Mission-Oriented Protective Postures (MOPP levels). In particular, missions were conducted in battle dress uniform and in full nuclear and chemical protective gear (MOPP4). The DNA team, on a noninterference basis, recorded detailed time and motion data for about 20 crew tasks. This report presents data on howitzer emplacement time, displacement time, time to first round, and time between rounds.

The M198 howitzer is a towed, 155 mm weapon and was manned by a ten-member U. S. Marine crew for this exercise. The crew consisted of a Chief of Section, a Gunner, an Assistant Gunner, a Radio Telephone Operator (or Recorder), and six Cannoneers. The six Cannoneers are the Number One Cannoneer, three projectile handlers, and two powder men. Table 1-1 summarizes the main tasks of the crew during a fire mission.

Table 1-1. Brief task descriptions for the crew of the M198 (155 mm) howitzer during fire missions.

Crew Member(s)	*Task Descriptions*
Chief of Section	Receive fire order and call projectile, charge, fuze, deflection and quadrant elevation (QE).
Gunner	Set deflection on sight, traverse tube/level bubble, check sight picture and level bubbles.
Assistant Gunner	Set QE on range quadrant and elevate tube/level bubbles.
Cannoneers	Load projectile and propellant. Close breech and prime firing mechanism. Attach lanyard. Open breech, swab and inspect bore.

Selection of times to be recorded was based primarily on the major task groups as represented in Table 1-1 and secondarily on the existence of readily discernible audible or visual cues for the human observers. A team of observers collected data in real time using notebook computers and appropriate software (McClellan, 1992). Table 1-2 outlines the recorded time points for the exercise.

Table 1-2. Events recorded for the M198 exercise.

Event	† = *Time Recording Points*
OVERALL ACTIVITIES	
Time reference mark	
MOPP4 entry	†
Move to firing point	† —
Conduct M198 emplacement	† ——— †
End of fire mission	†
Conduct M198 displacement	† — †
CHIEF OF SECTION	
Receive/call out fire mission	† — †
Standby	†
GUNNER	
Set deflection on sight*	† —
Traverse tube/level bubble	† — †
Check sight picture	† — †
ASSISTANT GUNNER	
Set QE on range quadrant*	† —
Elevate tube/level bubbles	† — †
Depress tube for loading	† — †
CANNONEERS	
Load start (set tray)	†
Ram projectile	†
Close breech; prime	† — †
Fire	†
Open breech/swab bore	† — †
RANGE SAFETY OFFICER	
Safety check	† — †

*The end of this task is marked by the beginning of the subsequent task.

The data presented and analyzed in this report, especially on the time to first round and the time between rounds during a fire mission, provides a detailed characterization of the overall rate of fire for the M198 howitzer. Results include the mean and standard deviation for both BDU and MOPP4. In addition, there is enough data to characterize the shape of the typical distribution of times for repeated trials and the dependence of standard deviation on the magnitude of the mean task time. Finally, since multiple fire missions were recorded over several hours, the data support a linear regression analysis giving rates of fire as a function of time in action.

SECTION 2
DESCRIPTION OF THE M198 EXERCISE

Three M198 crews spent two weeks each in this exercise. After a week of preparation, each crew conducted a series of fire missions for the record on Monday, Wednesday, and Friday of their second week. A day's planned exercise included 17 fire missions with a total of 89 inert rounds to be fired downrange. Table 2-1 presents the three mission scenarios used by the crews. The three scenarios are similar, consisting of the same 17 fire missions with minor variations in order. Each scenario begins with 7 fire missions totaling 30 rounds followed by a road march for resupply. Five of these first missions are *normal*, that is, the elevation angle is low enough that the barrel need not be depressed between rounds for reload. The other two fire missions are *high angle*, requiring the barrel to be depressed for reload.

After resupply, each scenario has 10 fire missions totaling 59 rounds. Nine of these are normal fire missions, ranging from 3 to 5 rounds each. The other fire mission is a *zone and sweep* mission consisting of 25 rounds. The aim point for each round of the zone and sweep is shifted to generate a 5-by-5 grid pattern for the laydown. The zone and sweep fire mission is the most demanding as far as sustained effort is concerned.

Table 2-2 presents the schedule of scenarios attempted by each crew and the results. In battle dress uniform (BDU), all three crews completed the scenarios as expected. Crew 1 repeated its BDU exercise on Friday (with a different scenario) because of technical difficulties with instrumentation on the howitzer on Monday, the first day of the exercise. Since the DNA team also made adjustments in its data taking procedures following the first day's experience, this report does not analyze the first day's data for Crew 1.

On one day for each crew, all operations were conducted at MOPP4 with standard crew positions and standard adjustments for loss of crew members (MOPP4-S). Crews 2 and 3 also conducted a day of operations at MOPP4 with an experimental, regimented rotation of crew positions designed to distribute the thermal-related work load more evenly across crew members (MOPP4-R). In addition to changing positions for the regimented rotation, one crew member was rotated into the shade for rest after each fire mission.

As part of the safety conditions of the exercise, medical personnel monitored the core temperature, heart rate, and skin temperature of each crew member while at MOPP4 to limit the amount of heat stress to be suffered by each. The first limitation was that a crew member's core body temperature should not rise above 39.4 degrees Centigrade. In addition, a crew member's heart rate should not exceed 160 beats per minute for more than five minutes at rest nor should it exceed 180 for more than five minutes at work. If any of these physiological conditions were exceeded by a crew member, he was withdrawn from operations and given medical attention. The remaining crew members then resumed operations with position adjustments as necessary. When only six crew members remained, the exercise was halted.

Table 2-1. Daily mission scenarios showing number of rounds planned for each fire mission.

Fire Mission Number	*Number of Rounds (Alternate Mission Scenarios)*		
	A	B	C
1	6	6	6
2	5 HA[1]	4	5 HA
3	4	5 HA	4
4	4	4	5 HA
5	5 HA	5 HA	4
6	3	3	3
7	3	3	3
Resupply and road march			
8	4	4	4
9	3	25 ZS[2]	3
10	25 ZS	3	5
11	5	5	25 ZS
12	5	5	3
13	3	3	3
14	3	5	5
15	5	3	3
16	3	3	3
17	3	3	5

[1]HA = High angle (elevation greater than 1000 mils)
[2]ZS = Zone and sweep

Table 2-2. Exercise summary for the P^2NBC^2 artillery test.

Date (1992)	*Crew*	*Weekday*	*Mission Scenario*	*Posture*[1]	*Scenario Completed*	*Fire Missions Completed*	*Rounds Fired*
10 Aug	1	Monday	A	BDU	Yes	17	89
12 Aug	1	Wednesday	C	MOPP4-S	No	7	30
14 Aug	1	Friday	B	BDU	Yes	17	89
17 Aug	2	Monday	A	BDU	Yes	16[2]	89
19 Aug	2	Wednesday	B	MOPP4-S	No	6	27
21 Aug	2	Friday	C	MOPP4-R	Yes	17	89
24 Aug	3	Monday	B	MOPP4-S	No	8+	42[3]
26 Aug	3	Wednesday	A	BDU	Yes	17	89
28 Aug	3	Friday	C	MOPP4-R	No	9	37
					Totals	114+	581

[1] BDU = Battle dress uniform
MOPP4 = Mission-Oriented Protective Posture, Level 4
-S = Standard positions with adjustments for missing crew members
-R = Regimented rotation of crew positions to distribute thermal work load

[2] On this day, rounds from mission 17 were lumped into mission 16 to meet a time deadline for cessation of firing.

[3] On Monday, Crew 3 operations were halted after partial completion of fire mission 9 (8 of 25 rounds fired).

For all three crews, the first scenario attempted at MOPP4 was with standard crew positions (MOPP4-S). None of the three crews were able to complete their scenario. Medical personnel pulled the fourth crew member, halting the exercise, after 6 to 8 fire missions. Crew 3 fired the most rounds, getting part way into their zone and sweep mission.

Only Crews 2 and 3 attempted a scenario in MOPP4 with regimented rotation (MOPP4-R). Crew 2 was highly motivated by SFC Thompson. They paced themselves well and were able to complete all 17 fire missions, although they were down to 7 crew members for the latter fire missions. Crew 3, on the other hand, completed fewer rounds for MOPP4-R than for MOPP4-S.

Table 2-3 presents the mission start, stop, elapsed times, and reason for termination. As procedures became routine, there was a general trend toward earlier start times. On only one day did operations halt before noon Eastern Daylight Time (EDT).

Table 2-3. Start, stop and total times for each day of the M198 exercise.

Day[1]	*Mission Start*[2]	*Last Round*	*Mission End*	*Reason for Termination*	*Total Elapsed Time*
C1M	10.6272	15.9125	16.2561	Normal	5.629 = 5h 38m
C1W	10.2944	12.3767	13.20	Medical	2.906 = 2h 54m
C1F	9.6672	13.5925	13.7772	Normal	4.11 = 4h 7m
C2M	10.1508	14.0078	14.00	Range Safety	3.857 = 3h 51m
C2W	9.6656	11.3967	11.433	Medical	1.768 = 1h 46m
C2F	9.5894	15.7303	16.0047	Normal	6.415 = 6h 25m
C3M	9.7183	14.9169	14.9333	Medical	5.215 = 5h 13m
C3W	9.0956	13.3503	13.5775	Normal	4.482 = 4h 29m
C3F	9.0814	13.1069	13.15	Medical	4.069 = 4h 4m

[1]See Table 2-2 for dates. C1M = Crew 1, Monday, etc.

[2]All times except the last column are clock time (EDT) expressed in decimal hours.

Table 2-4 summarizes meteorological data for each of the exercise days. Two sets of temperature, humidity, and wind speed data are shown, representing the 15 minute report nearest the exercise start time and that nearest the exercise finish or halt time. The last two columns show the elapsed time for the day's exercise and the average solar insolation during the exercise. The solar insolation is expressed as the number of watts of sunlight falling on a square meter of level ground. The average was calculated by integrating a cubic spline curve fitted to hourly average insolation values reported from a nearby meteorological station. Appendix A includes plots of hourly insolation.

Since the crew was not using a camouflage net, they were for the most part working in direct sunlight. Monday for Crew 2 (C2M) was a rainy day. Friday for Crew 2, when they completed their MOPP4-R scenario, was the sunniest day but had the lowest combination of temperature and humidity.

Table 2-4. Meteorological summary for the exercise days (Zubal, 1992).

	Starting Conditions			*Ending Conditions*			*Average Solar Insolation*	
Crew	*Temp*	*Hum*	*Wind Ave/Pk*	*Temp*	*Hum*	*Wind Ave/Pk*	*Time Interval*	*Insolation*
	F	*%*	*kt*	*F*	*%*	*kt*	*EDT*	*W/m²*
C1M	82	71	5/10	88	58	6/11	10.63 - 16.26	747
C1W	77	81	--	79	80	--	10.29 - 13.20	691
C1F	68	90	3/7	74	79	2/6	9.67 - 13.78	440
C2M	70	92	3/7	72	92	3/5	10.15 - 14.00	148
C2W	76	81	3/6	81	63	2/8	9.67 - 11.43	653
C2F	70	71	3/7	77	54	4/6	9.59 - 16.00	815
C3M	75	84	3/5	81	63	2/8	9.72 - 14.93	784
C3W	79	86	3/4	89	63	4/7	9.10 - 13.58	635
C3F	77	90	5/9	85	71	11/19	9.08 - 13.15	631

SECTION 3
DATA CHARACTERISTICS

As described elsewhere (McClellan, 1992), events to be timed were divided among three principal human observers (data loggers) each with a notebook computer. Event times were digitally recorded from the internal clock of each computer at the stroke of keyboard letters assigned to each event. On certain days, fourth and sometimes fifth data loggers provided redundant measurements for one or two of the three principal loggers. Figure 3-1 shows the event timelines for a sample mission according to the raw data generated by the three principal loggers.

Data reduction consists of several phases. First, the data from all computers must be corrected to the same time scale. Secondly, redundancies and errors in event measurements among the 3 to 5 human observers must be reconciled to provide a single master data file for each mission. Finally, the statistical properties of the data must be examined to guide further analyses.

3.1 COMPUTER CLOCK SYNCHRONIZATION.

All computer clocks were manually synchronized each morning prior to the start of the exercise. With care, the manual synchronization can be accurate within a few tenths of a second, but sometimes larger errors occurred. As a back up procedure, time reference marks were generated during the exercise. Furthermore, all data loggers recorded the firing of the howitzer, cueing primarily on the muzzle blast. With the reference marks and firing data, synchronization can be achieved within a few hundredths of a second and relative drift of the clocks can be removed from the data.

Figure 3-2 illustrates how the reference and firing data is used to find the offset between the clocks of two observers. The example is for the first 7 fire missions of Crew 1 on Wednesday, 12 August 1992 (data set *C1W1*). The figure shows the difference (offset) in recorded reference and firing times between Logger 2 and Logger 1 plotted versus Logger 2 time. The dashed line is a linear regression of offset versus time. It shows that the clock of Logger 2 was running slower than that of Logger 1, loosing about 1 second every 2 hours. A linear offset according to the formula shown in Figure 2-2 was used to correct the times recorded by Logger 2 so that they agree with the clock of Logger 1. The same procedure was used for all data sets so that all times for further analysis are synchronized to the clock of Logger 1.

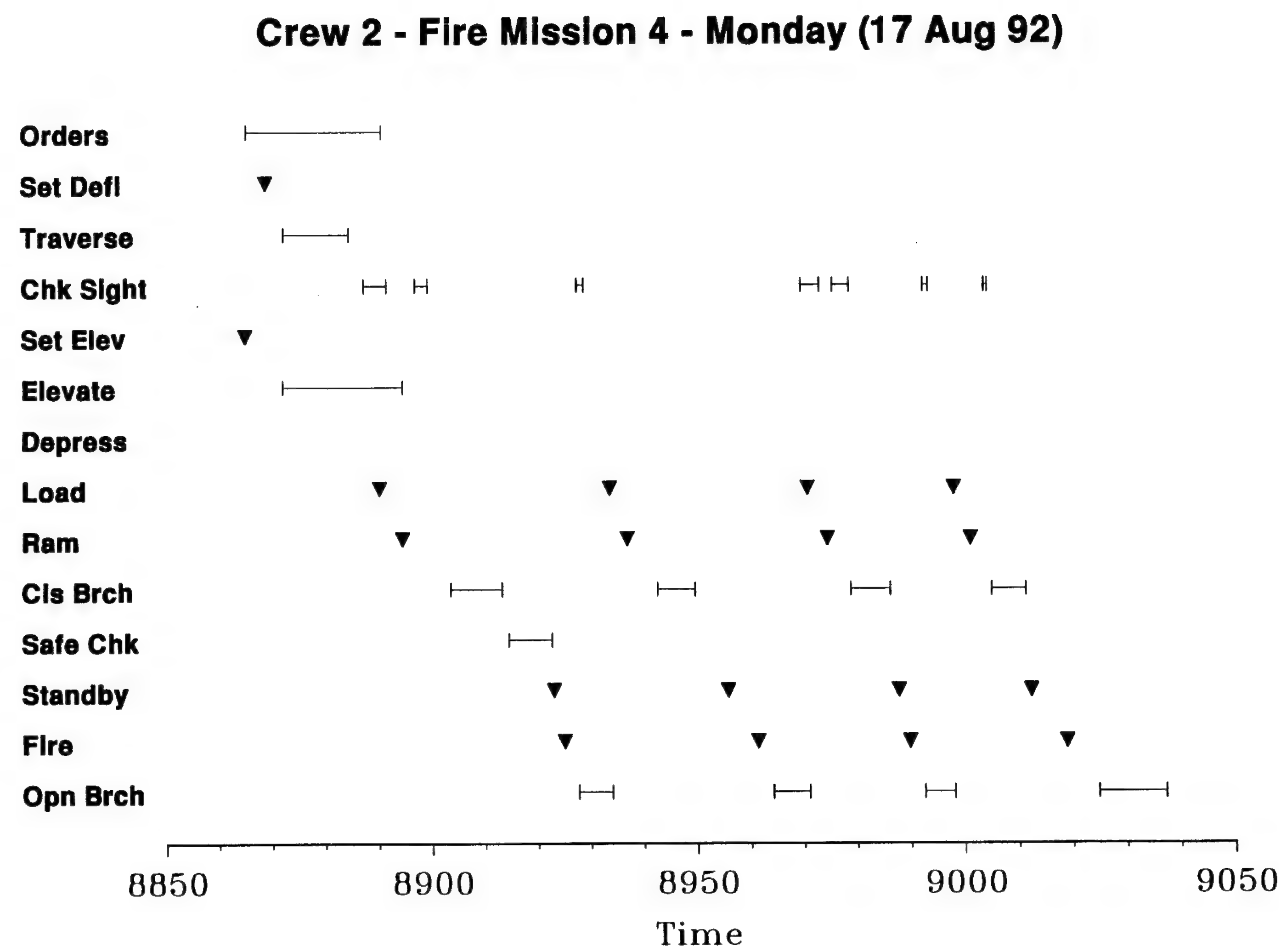

Figure 3-1. Sample event timelines for crew 2, fire mission 4; raw data.

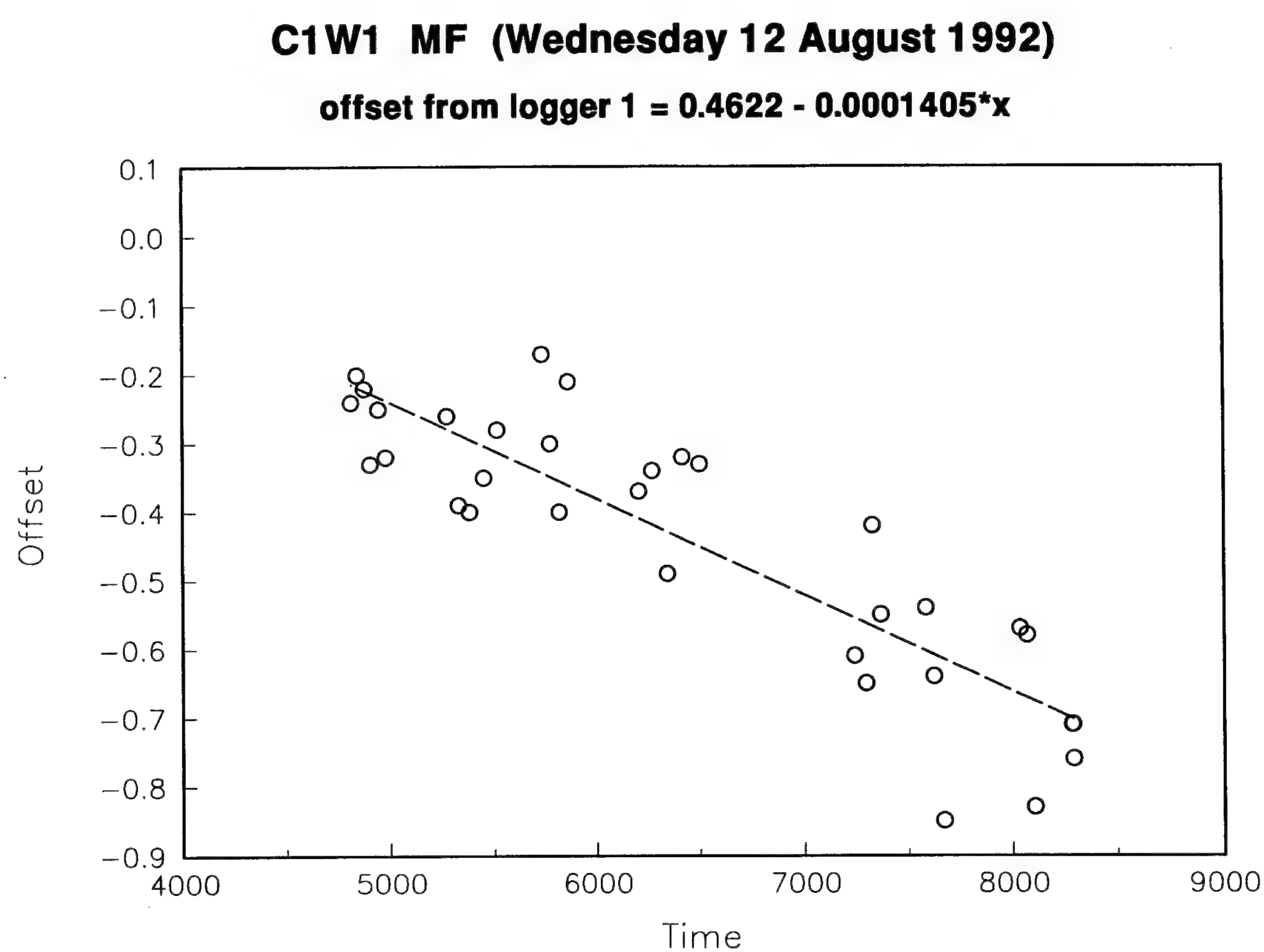

Figure 3-2. Sample offset plot of firing times logged by one observer relative to another (Logger 1). Time and offset are in seconds. Dashed line is from linear regression analysis.

Only two of the computers were of the same make and model. These two showed minimal drift between their clocks. The example in Figure 3-2 shows one of the worst cases of relative drift between different computers. It should be noted the observers and computers were not in a controlled environment. The computers sat on unsheltered tables for four to eight hours exposed to the varying sunlight, heat, and humidity of the August weather in Aberdeen. Over periods of four to six hours, we sometimes observed nonlinear drift between computer clocks, probably from unequal thermal conditions or temperature coefficients of the computers. During the limited periods of time occupied by the seven fire missions before resupply or the ten missions after resupply, a linear regression was always sufficient.

3.2 RECONCILIATION OF RECORDED FIRING TIMES.

The recorded firing times after correction for clock differences provide an illustration of the accuracy with which human observers can record event times with push buttons. Firing times for each of the 581 rounds during the 3 week exercise were recorded by 3 to 5 observers. For each round, a mean of the recorded times and a standard deviation were calculated. Figure 3-3a shows the frequency distribution of these individual standard deviations in 0.01 second bins. The tail of the distribution (some of which is off scale) results from inattention of one observer or another.

Since it is clear from Fig. 3-3a that observers usually record times within a tenth of a second of each other, the presence of one or more outliers is assumed if any recorded value differs by more than 0.1 second from the mean of all recorded values for a given round. For each round with an outlier according to this criteria, the worst outlier in each group is removed iteratively until the remaining values each fall within 0.1 s of their mean. Fortunately, in all cases, at least two measurements are left after this procedure for every round fired. In other words, there were always at least two loggers who agreed within 0.2 s. The mean times after removal of outliers are used as the estimate of the correct firing time for all further analyses. Figure 3-3b shows the distribution of standard deviations after the removal of outliers. No values were off scale.

It is possible for two observers to agree within 0.2 s and still both be wrong. However, the narrowness of the distribution in Fig. 3-3b indicates that multiple observers usually agreed within a few hundredths of a second. The only plausible explanation for such agreement is that the observers consistently cued on the actual firing of the howitzer. This conclusion is not surprising since, with the observers at a distance of about 30 m from the howitzer, the firing was difficult to ignore.

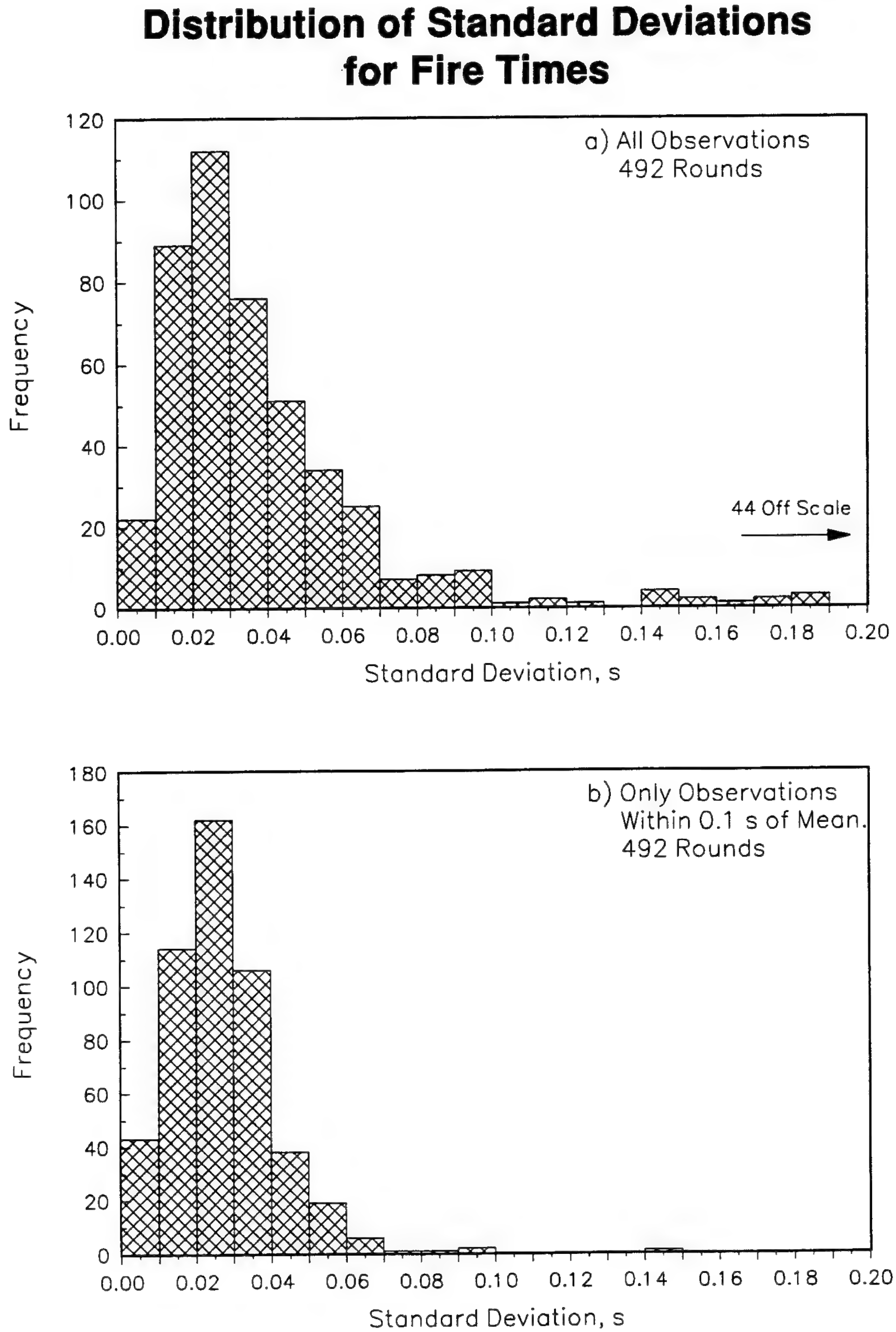

Figure 3-3. Frequency distribution of the standard deviation of firing times recorded by multiple observers for each round, a) all observations included for each round and b) with elimination of outliers.

The remaining caveat is that all measured values will lag behind the actual firing time by the average fine motor response time of the team of observers. Human response times are in the range of 0.12-0.16 s for auditory signals and 0.15-0.20 s for visual signals (Van Cott and Kinkade, 1972). Since only time differences are analyzed in this effort, even this small lag will tend to cancel out.

In summary, mean firing times are accurate within about 0.1 s relative to the clock of Logger 1 and, because of cancellation of observer lag times, differences between firing times are accuratewithin about 0.05 s. This uncertainty is much smaller than the variation of time between rounds from other factors, so measurement uncertainty may be neglected for time between rounds.

3.3 RECONCILIATION OF OTHER EVENT TIMES.

There was much less redundancy of measurement for event times other than the firing of the howitzer. For example, calculation of time-to-first-round (TTFR) for each fire mission requires three event times in addition to the time of the first round, namely, 1) the initiation of the fire mission (receipt of orders), 2) the beginning of the safety check, and 3) the end of the safety check.

There was usually only one measurement for the initiation of the fire mission; however, it may be cross checked within a few seconds by comparison with the initiation of *set deflection* and *set quadrant elevation* by the Gunner and the Assistant Gunner, respectively. These crew members usually began their tasks with the receipt of orders electronically on their gun display units (GDU's), the same electronic signals that cued the verbal orders used for our recording.

The start of the safety check is essentially coincident with the time at which the No. 1 Cannoneer finishes the *close breech; prime* task, providing at least one redundant measurement. The end of the safety check is essentially coincident with the *standby* event, also providing at least one level of redundancy. Of course, when two values disagree, it is not always clear which is in error. The data were reconciled by hand, allowing discrepancies of less than a second between these essentially coincident events. If the discrepancy was more than 1 second, the values were brought into agreement by making judgement calls as necessary. An audit trail of such changes provides quality control during data analysis.

Since most redundant measurements associated with the beginning and end of the safety check agree to better than 1 second, the root mean square (rms) measurement error is less than 1 second. Quantitative estimates of the observer error for time-to-first-round have not been made. However, an upper limit can be estimated by assuming that measurements of the start of the fire mission, the start of the safety check, and the end of the safety check each independently have an rms error less than 1 second. These independent uncertainties combine in the calculation of time-to-first-round to give a root mean square uncertainty less than 1.7 seconds.

3.4 STATISTICAL PROPERTIES OF THE DATA.

Statistical properties of the task time data must be considered before detailed analysis is undertaken. Two questions arise regarding time measurements of the same task sequence being performed repeatedly by different crews under varying conditions. The first question is whether the performances observed in two or more trials are equivalent, that is, are the observed mean times consistent among trials. The analysis of variance (ANOVA) test provides a quantitative answer but requires that the data sets under consideration have equal variance (square of the standard deviation) and be normally distributed within each data set.

If the variance is a known function of the mean, then the data may be transformed before analysis to generate data sets with equal variance. Table 3-1 shows recommended transformations for various types of data. These transformations will also usually improve the normality of the data. Is one of these transformations appropriate for the M198 data?

Table 3-1. Recommended transformations to equalize the variance of data samples when the variance has a power law dependence on the mean (Alder and Roessler, 1964).

Power of the Mean	*Recommended Transformation*
1	Square root
2	Logarithm
4	Reciprocal

The second question arises in conjunction with regression analyses to test for systematic variation of performance with respect to a parameter such as time-at-MOPP4. Linear regression, strictly applied, requires that the measured dependent variable have a normal (Gaussian) distribution about its mean. If the recorded data is not distributed normally, then it is sometimes possible to find a mathematical transformation of the data that generates a normally distributed dependent variable. Should the M198 data be transformed before regression?

Fortunately, examination of the data on time between rounds and time to first round indicates that a logarithmic transformation is an acceptable answer to both questions.

3.4.1 Dependence of Variance on the Sample Mean.

Comparable data sets with different means are required to examine the dependence of the variance of a sample of measured times on the mean of the sample. In addition, the mean value for each data set must remain fairly constant during the repetitions which produced the set. Much of the M198 data does not satisfy this criteria; the time to perform a task sequence tends to either shorten with practice or lengthen with accumulated heat stress and fatigue. Data sets

that do not show these effects to a significant degree must be used.

Table 3-2 lists 10 data sets that have reasonably stable means over time. The sets were selected from data on time-to-first-round and time-between-rounds as presented in Sections 5 and 6. For judging stability, outliers due to crew member missteps or unusual events were removed before regression to concentrate on typical rather than abnormal variations in performance. Regression analyses for these 10 data sets showed no time dependence at the 5% level of significance (probability of F > 0.05 for each data set). Table 3-2 lists the mean and variance of these ten data sets as well as the logarithms (base 10) of these values.

Table 3-2. Mean and variance for data sets with stable means.

Crew/Data	*Mean*	*Sum Sq*	*Number of Obs*	*Var*	*Prob f*	*Log (var)*	*Log (mean)*
c1-tbr-bdu	24.06	269.47421	36	7.48539	0.45226	0.87421	1.38140
c1-tbr-ms	38.35	751.90985	15	50.12732	0.29112	1.70007	1.58383
c3-tbr-ms	45.88	1415.84338	15	94.38956	0.54702	1.97492	1.66169
c2-tbr-mr	43.19	637.94287	25	25.51771	0.99998	1.40684	1.63539
c2-tfr-bdu	47.33	325.81100	13	25.06238	0.41844	1.39902	1.67515
c3-tfr-bdu	46.88	870.19727	14	62.15694	0.05344	1.79349	1.67103
c2-tbr-mr-zs	48.76	1390.78784	24	57.94949	0.37460	1.76305	1.68810
c1-tbr-b-zs	26.74	208.49001	24	8.68708	0.55906	0.93887	1.42728
c2-tbr-b-zs	30.43	370.71460	23	16.11802	0.96665	1.20731	1.48343
c3-tbr-b-zs	22.30	161.05911	22	7.32087	0.06414	0.86456	1.34839

Figure 3-4 shows a log-log plot of variance versus mean and Table 3-3 lists statistical data for the linear regression plotted in Figure 3-4. The regression shows that the variance is proportional to the (2.8 ± 0.5) power of the mean. At the 5% level of significance, this value is consistent with 2 and not with 4. Thus, of the transformations listed in Table 3-1, the logarithm is the best choice.

DATA SETS WITH STABLE MEANS (NO TIME DEPENDENCE)

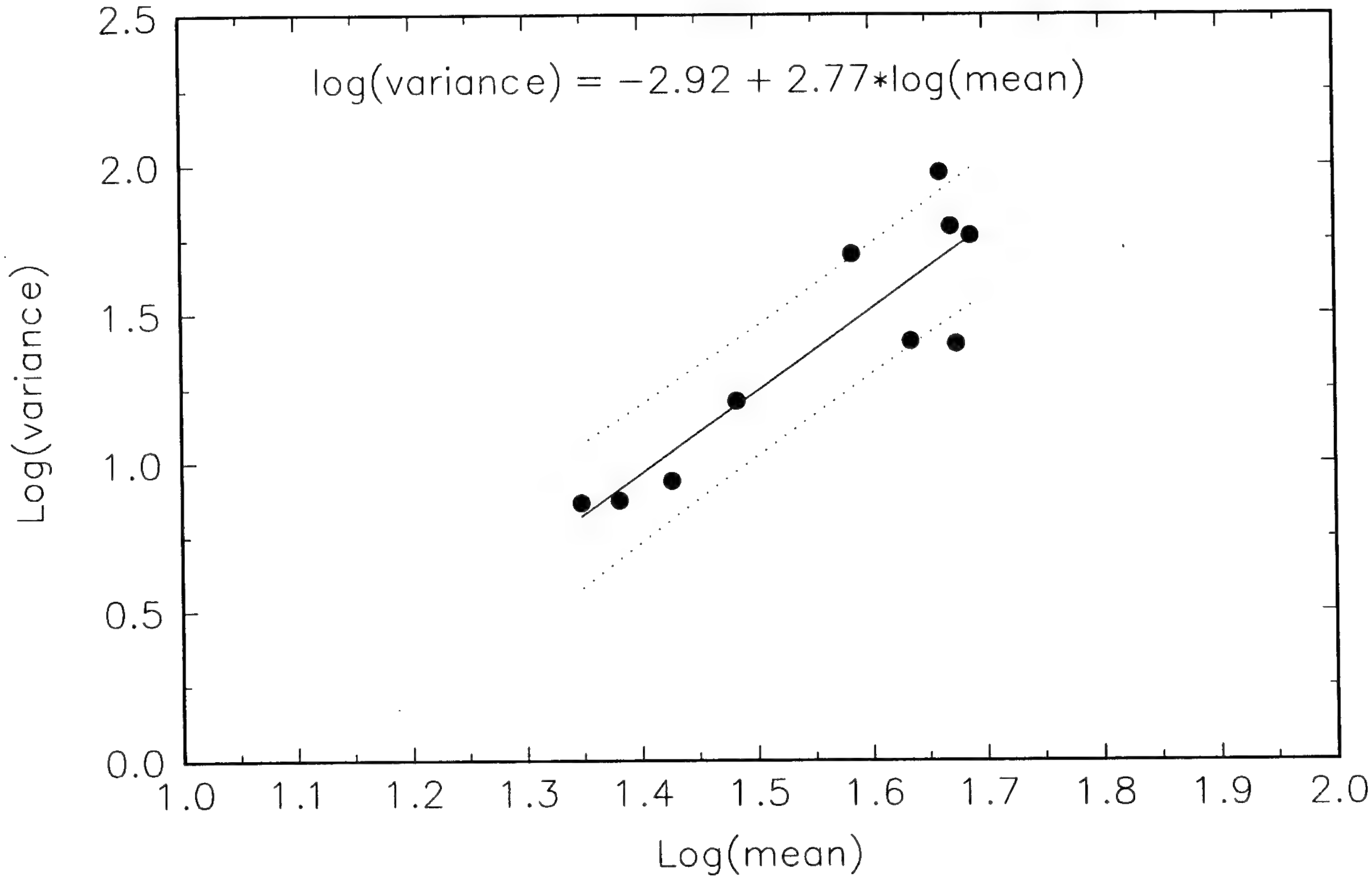

Figure 3-4. Linear regression of the data from Table 3-2 on a log-log plot shows that the sample variance changes as the 2.8 ± 0.5 power of the sample mean.

Table 3-3. Statistical summary and regression analysis for data sets with stable means.

For all crews: log(variance) = constant + slope*log(mean)

Mean of Dependent Variable	1.39224
Number of Observations	10
Total Sum of Squares	1.51958
Residual Sum of Squares	0.30386
Std. Dev. of Estimate	0.19489
R-squared	0.80004
Adjusted R-squared	0.77504
Degrees of Freedom (df)	8
Number of Ind Vars (K)	2
F(K-1, df)	32.00738
Prob. Value of F	0.00048
Constant	-2.91533
Standard error	0.76388
Slope	2.76912
Standard error	0.48946
t-ratio	5.65751
prob t	0.00048
Correlation Coefficient	0.89445

3.4.2 Normality of the Data.

In principle, normally distributed data extends to positive and negative infinity symmetrically about its mean. In practice, for reasonably sized data sets, there is little chance to observe values beyond a few standard deviations from the mean. Sometimes, there is a physical limit which constrains observed values. For example, time intervals cannot be less than zero. When this physical limit is within a few standard deviations of the mean of a sample, then departures of normality will be observed, usually as an asymmetry of the data about its mean.

For task times whose mean is within a few standard deviations of zero or some other limiting minimum time, the tail of the distribution toward shorter times will be suppressed and the tail toward longer times will be enhanced. The logarithmic transformation may be useful in this circumstance since the logarithms of a set of positive numbers may range over both positive and negative values. The new variable defined by the logarithm of the measured task times can have a symmetric distribution about its mean.

The chi-squared test may be used to measure how well the distribution of a data set matches

the normal distribution. The next paragraphs describe tests of the normality of the data of Table 3-2 both directly (untransformed times) and as logarithmic values.

The data of Table 3-2 is aggregated to provide better statistical accuracy for the test of normality. Figure 3-4 demonstrates that the standard deviation (or width) of the data distributions of individual sets is approximately proportional to the mean of the set, since the standard deviation is the square root of the variance. Therefore, the data sets may be superposed by dividing each individual time by the mean of the set to which it belongs. This scaling brings all ten data sets to a mean of 1.0 with approximately equal standard deviations.

Figure 3-5a compares this aggregate distribution, plotted as a histogram, to a normal curve with the same mean and variance. The aggregate distribution is not symmetric about its mean and has less than a 1% chance as measured by the chi-squared test of matching the normal distribution. As expected, the aggregate distribution is asymmetric with a bigger tail toward longer times.

Next, the distribution of logarithmic values is tested for normality. First the data is transformed by taking the logarithm of all measured time intervals. According to Table 3-1, this transformation for the data of Table 3-2 will result in data sets with equal variance, that is, the distributions for the ten data sets will have approximately equal widths on a logarithmic plot. Thus, superposing the ten distributions of logarithmic data only requires an additive shift on a logarithmic plot. (It is relatively easy, for the mathematically inclined, to prove that the inverse process of starting with a single distribution in logarithmic space, shifting it by various displacements while keeping a fixed width, and then transforming each distribution back to straight time values will result in a series of time distributions whose variances are proportional to the square of their means.)

Figure 3-5b shows the superposed data obtained by shifting each logarithmic data set to a mean of zero. A normal curve with the same mean and variance matches the data quite well. The chi-squared test indicates a 13% confidence level that the data matches the normal distribution. This agreement is reasonable given the diversity of the data sets being superposed. It will be valuable in later analyses of individual task times to address the question of normality again with more homogeneous data.

In the meantime, this report assumes that all data is *log normal*, that is, taking the logarithm of all measured time intervals provides reasonably normal distributions. Also, the logarithmic transformation generates data sets with approximately equal variance. For ANOVA tests and regression analyses, each measured time interval will be represented by its logarithm. Linear regression analyses will be compared to data on semilogarithmic plots where the regression lines are straight. As another benefit of the logarithmic transformation, confidence bands encompass only positive time intervals.

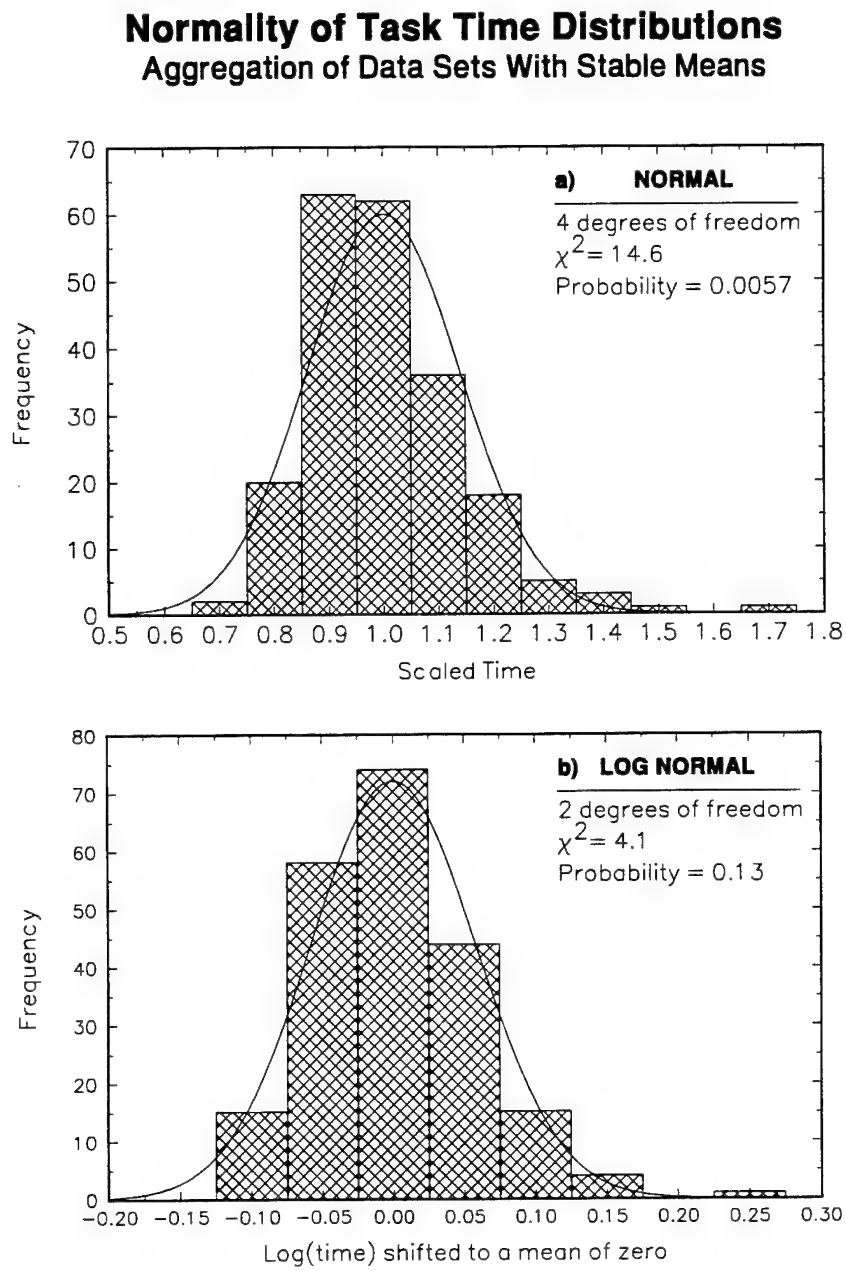

Figure 3-5. Chi-squared test for normality shows that task time distributions are a) not consistent with a normal distribution but b) are reasonably consistent with a log normal distribution.

SECTION 4
EMPLACEMENT AND DISPLACEMENT TIMES

For howitzer emplacement and displacement, activities timed were the move to the firing point, two phases of emplacement, and an overall displacement time.

There was an evolution of emplacement and displacement procedures during the test to offset serious delays introduced by range safety protocols. The procedure finally involved two howitzers: an instrumented and surveyed howitzer left in place for fire missions and a surrogate (spare) howitzer for emplacement and displacement activities.

A staff member of Aberdeen Proving Grounds, SFC John Thompson, acted as Chief of Firing Battery for each crew during the exercise. In preparation for the start of the exercise, the truck carrying the M198 crew and towing the surrogate howitzer would come to a standard parking place along the road leading to the firing point. When all was ready, at SFC Thompson's signal, the truck moved about 100 m to a surrogate firing point. After emplacement of the surrogate gun, the crew moved about 50 m to the previously positioned and surveyed firing gun to conduct fire missions, thereby avoiding nonoperational delays for the safety crew to check lay and emplacement of the howitzer. At the completion of fire missions, the crew moved back to the surrogate howitzer for displacement.

The *drive to firing point* interval was started when the truck was signaled to proceed from its initial parking place and ended when the truck stopped at the emplacement point. After resupply, the crew followed the same emplacement procedure as in the morning and the drive to the firing point was timed in the same manner.

Initially, the truck approached the firing point with a U-turn through soggy ground adjacent to the firing point. Because the truck got stuck in the mud on two occasions, the procedure was changed on 21 August (C2F) to a straight line approach avoiding wet ground. Only the data for the straight line approach is used here for calculating performance.

The first phase of emplacement activity was laying the howitzer. This interval started when the truck came to a stop at the emplacement point and the troops jumped up to dismount. The interval ended when SFC Thompson declared the gun *laid.* This time was usually about four minutes. It encompasses the time necessary to ready the gun to receive and execute the first fire mission, but includes neither unloading ammo from the truck nor continued improvement of position. SFC Thompson usually called out a longer time for the gun to be *in order* but this time was not measured by the DNA team.

The second phase of emplacement activity encompassed the process of unloading, stacking, and covering the projectiles and propellant near the firing gun. While the surrogate gun was still being brought to order by other crew members, the driver and cannoneers would move to the firing gun with the truck to do their work. The *prepare ammo* interval was started when the tailgate of the truck was brought down at the firing gun. The interval was ended when the two

ammo tarps were in place over iron stakes to cover the physically separated stacks of powder and projectiles.

After the conclusion of fire missions, the displacement time, that is, the time to pack up and move out was recorded. The interval was started when the *close station, march order* (CSMO) was given immediately after the last fire mission. Equipment was loaded back onto the truck at the firing gun, then the driver moved the truck to the surrogate gun which was already being prepared for displacement by other crew members. The displacement interval was ended when all crew members were mounted and the truck was ready to roll with the spare gun in tow. The crew did not actually depart at this point. They were required to dismount again for a final mood assessment questionnaire before leaving the area.

The measured times in seconds for all of the emplacement/displacement activities for each crew are listed in Tables 4-1 through 4-4. Because of variations in procedure discussed above, only selected measurements are used for final comparisons between times in BDU and MOPP4. Measurements not used are enclosed in parentheses in each Table. Note that for the emplacement and displacement activities there is no difference between the MOPP4 days designated as MOPP4-S and MOPP4-R.

Table 4-1. Times in seconds for emplacement activities in battle dress uniform. Values in parentheses not used for performance calculations shown in Table 4-5.

Crew/Day	*Drive to Firing Point*		*Lay Howitzer*	
C1F-a	(66.5)	U-turn	(470.)	First day with surrogate gun
C1F-b	(67.4)	U-turn	(543.)	First day with surrogate gun
C2M-a	(1830.2)	U-turn (stuck)	220.	
C3W-a	33.3	Straight line	252.	
C3W-b	43.0	Straight line	263.	

-a: first emplacement of the day

-b: second emplacement (after resupply)

Table 4-2. Times in seconds for further emplacement/displacement activities in battle dress uniform. Values in parentheses not used for performance calculations shown in Table 4-5.

Crew/Day	*Ammo Set Up*	*Displacement*	
C1F-a	--	481.	First day with surrogate gun_
C1F-b	--	(634.)	First day with surrogate gun_
C2M-a	--	--	Range safety halt
C3W-a	1256.	607.	Surrogate gun
C3W-b	1450.	(726.)	Surrogate gun

-a: first emplacement/displacement of the day

-b: second emplacement/displacement (after resupply)

Table 4-3. Times in seconds for emplacement activities in MOPP4. Values in parentheses not used for performance calculations shown in Table 4-5.

Crew/Day	*Drive to Firing Point*		*Lay Howitzer*	
C1W-a	(77.8)	U-turn	234.	Firing gun
C2W-a	(86.9)	U-turn	188.	Surrogate gun
C2F-a	(71.5)	Straight line	241.	Surrogate gun
C2F-b	(61.3)	Straight line	313.	Surrogate gun
C3M-a	34.3	Straight line	373.	Surrogate gun
C3M-b	49.2	Straight line	401.	Surrogate gun
C3F-a	32.3	Straight line	227.	Surrogate gun
C3F-b	29.6	Straight line	333.	Surrogate gun

-a: first emplacement of the day

-b: second emplacement (after resupply)

Table 4-4. Times in seconds for further emplacement/displacement activities in MOPP4. Values in parentheses not used for performance calculations shown in Table 4-5.

Crew/Day	*Ammo Set Up*	*Displacement*
C1W-a	--	731.Firing gun
C2W-a	1139.	--Surrogate gun
C2F-a	1395.	1050.Surrogate gun
C2F-b	3172.	(965.) Surrogate gun
C3M-a	1163.	1026.Surrogate gun
C3M-b	2452.	--Surrogate gun
C3F-a	1477.	818.Surrogate gun
C3F-b	2146.	--Surrogate gun

-a: first emplacement/displacement of the day

-b: second emplacement/displacement (after resupply)

Table 4-5 summarizes the average times for each of the four emplacement/displacement activities in BDU and MOPP4. Averages are obtained from the values listed in Tables 4-1 to 4-4 that are not enclosed by parentheses. Values enclosed in parentheses are good measurements but not used for reasons discussed below. Performance in MOPP4, defined to be the baseline task completion time in BDU divided by the task completion time in MOPP4, is used to compare task times in BDU and MOPP4. Assuming that MOPP4 slows task completion, this task time ratio will lie between one and zero. Table 4-5 lists the performance for each task.

Table 4-5. Summary of average task times and performance for the emplacement/displacement activities.

Task	*BDU Baseline Task Time*	*Task Time in MOPP4*	*Elapsed Time in MOPP4*	*Performance Ratio*
Drive to Firing Point	38 ± 7 s	36 ± 4 s	0-3 h	1.05 ± 0.23
Lay Howitzer	245 ± 13 s	253 ± 31 s 349 ± 27 s	0.1 h 3.4 h	0.97 ± 0.13 0.70 ± 0.07
First Ammo Set UP, 30 Rds	1256 s	1294 ± 84 s	0.4 h	0.97 ± 0.06
Second Ammo Set Up, 59 Rds	1450 s	2590 ± 300 s	3.6 h	0.56 ± 0.06
Displacement for Resupply	544 ± 90 s	906 ± 80 s	2.1 h	0.60 ± 0.11

For all except the baseline times for ammo set up, there are two or more measurements of each task time. The average times listed in Table 4-5 are accompanied by a standard error of the mean except that when only two measured values are available, their standard deviation is quoted. The uncertainty in the performance ratio is calculated under the assumption that uncertainties for BDU and MOPP4 are independent. The uncertainties are a useful guide for interpreting the performance ratios but should not be taken too literally because of the relatively small number of measurements on which they are based.

The times for the straight line drive to the firing point before and after resupply have been aggregated since there is no obvious difference between them either in BDU or at MOPP4. In fact, there is no statistically significant difference between the times with and without MOPP4, although a 10% or 20% degradation is not ruled out. The large uncertainty in the performance ratio indicates that variance in driving time was due predominately to factors other than MOPP gear.

The baseline time for laying the howitzer consists of the three measurements for Crews 2 and 3. The Friday measurements for Crew 1 are unusually long and are not used since Friday was the first day using a surrogate gun for emplacement. All five measurements of times to lay the howitzer for the first mission of the day are used for the MOPP4 average time. The average time-in-MOPP4 for these intervals was 0.1 h as indicated in Table 4-5. The measured times to lay the howitzer after resupply were significantly longer those before the first mission of the day; their average is quoted separately in Table 4-5. The average time-in-MOPP4 for laying the howitzer after resupply was 3.4 h. The performance ratio for laying the howitzer at MOPP4 is not significantly different from unity after 0.1 h in MOPP4. On the other hand, after resupply at 3.4 hour time-in-MOPP4, the performance ratio is degraded about 30% to a value of 0.70 ± 0.07. The relatively small uncertainty indicates a good confidence level for this measured degradation.

The times for ammo set up are quoted separately for the first set up of the day and the set up after resupply since the number of rounds to be handled was twice as large after resupply. There was only one measurement of BDU baseline for each of the set ups, so no uncertainty can be quoted. There are four measurements of the first set up of the day (30 rounds) in MOPP4 and three measurements of the set up after resupply (59 rounds) providing good confidence in these times. The performance ratio of 0.97 ± 0.06 for the set up after 0.4 h time-in-MOPP4 indicates no measured performance degradation for this physically demanding task. Stated more formally, the measurement of the performance after 0.4 h in MOPP4 indicates with 95% confidence that the performance is better than 0.85 (two standard deviations below 0.97). On the other hand, the measured performance ratio for the ammo set up after resupply, after an average time-in-MOPP4 of 3.6 h, is 0.56 ± 0.06 indicating a substantial degradation. There is 95% confidence that the performance ratio is below 0.68 (two standard deviations above 0.56).

Only one crew on one day managed to finish an entire scenario of 17 fire missions in MOPP4

and conduct a second and final displacement. Therefore, Table 4-5 shows average displacement times only for the first displacement just before resupply. There are two measurements in BDU shown in Table 4-2 and there are four measurements in MOPP4 as shown in Table 4-4. These displacements in MOPP4 just before resupply occur after an average time-in-MOPP4 of 2.1 h. The performance ratio is 0.60 ± 0.11 indicating with 95% confidence that the performance is degraded below 0.82.

In summary, the data presented in this section indicates minimal performance degradation in the first half hour of donning MOPP4 for the two emplacement tasks of laying the howitzer and setting up ammo stacks. On the other hand, after 2 to 4 hours in MOPP4 there are significant degradations of 30% to 40% for laying the howitzer, ammo set up, and displacement. Finally, for the relatively simple task of a short (35-second) straight line drive to the firing point, there is no degradation measured even after 3 hours in MOPP4.

SECTION 5
TIME TO FIRST ROUND

The time to first round (TTFR) for each fire mission is the time interval between start of orders for the fire mission and the firing of the first round of the fire mission. The TTFR can be less than 40 seconds for a well-functioning crew in battle dress uniform.

Initial indication of a fire mission comes from a shrill tone sounded by the RTO's communications equipment. There is some delay, usually only a second or so, for the crew to respond to the tone. Because of occasional nonoperational delays in crew response, the TTFR interval was started for these measurements when the first crew member shouted *fire mission* rather than when the communications tone sounded.

Range safety procedures required a pause just before the first round of each fire mission for the range safety officer to check the aiming of the gun. This safety check interval was timed separately and is subtracted from the TTFR's presented here.

The following subsections present time-to-first-round data for the three types of fire missions, 1) normal, 2) high angle, and 3) zone and sweep. For each mission type, TTFR is reported for three conditions: battle dress uniform (BDU), MOPP4 with standard crew positions (MOPP4-S), and MOPP4 with regimented rotation of positions (MOPP4-R). All fire missions are *fire-for-effect* missions.

5.1 NORMAL FIRE MISSIONS.

This subsection presents a detailed description of the data, the analytical procedures, and the resulting Figures and Tables for normal fire missions, that is, those with elevation angle less than 1000 milliradians and with 3 to 6 rounds on a single aim point. Unless otherwise indicated, the same explanations and caveats apply to the high angle and the zone and sweep missions presented later.

5.1.1 Battle Dress Uniform.

As explained in Section 2, only the second day of BDU data for Crew 1 is being analyzed. Therefore, we have one day of BDU data for each crew. Figure 5-1 presents the TTFR data for the normal missions for each crew separately. TTFR in seconds is plotted versus *scenario time* in hours. Scenario time is the elapsed time since the beginning of the day's exercise as marked by the signal to start the drive to the firing point for the first emplacement of the day. After resupply, scenario time is still referenced to the beginning of the first emplacement of the day. Each scenario had 5 normal fire missions before resupply and 9 after. The resupply interval of an hour or so with no rounds fired is apparent in Figure 5-1. When MOPP gear is worn, time-in-MOPP4 is just a few minutes longer than scenario time.

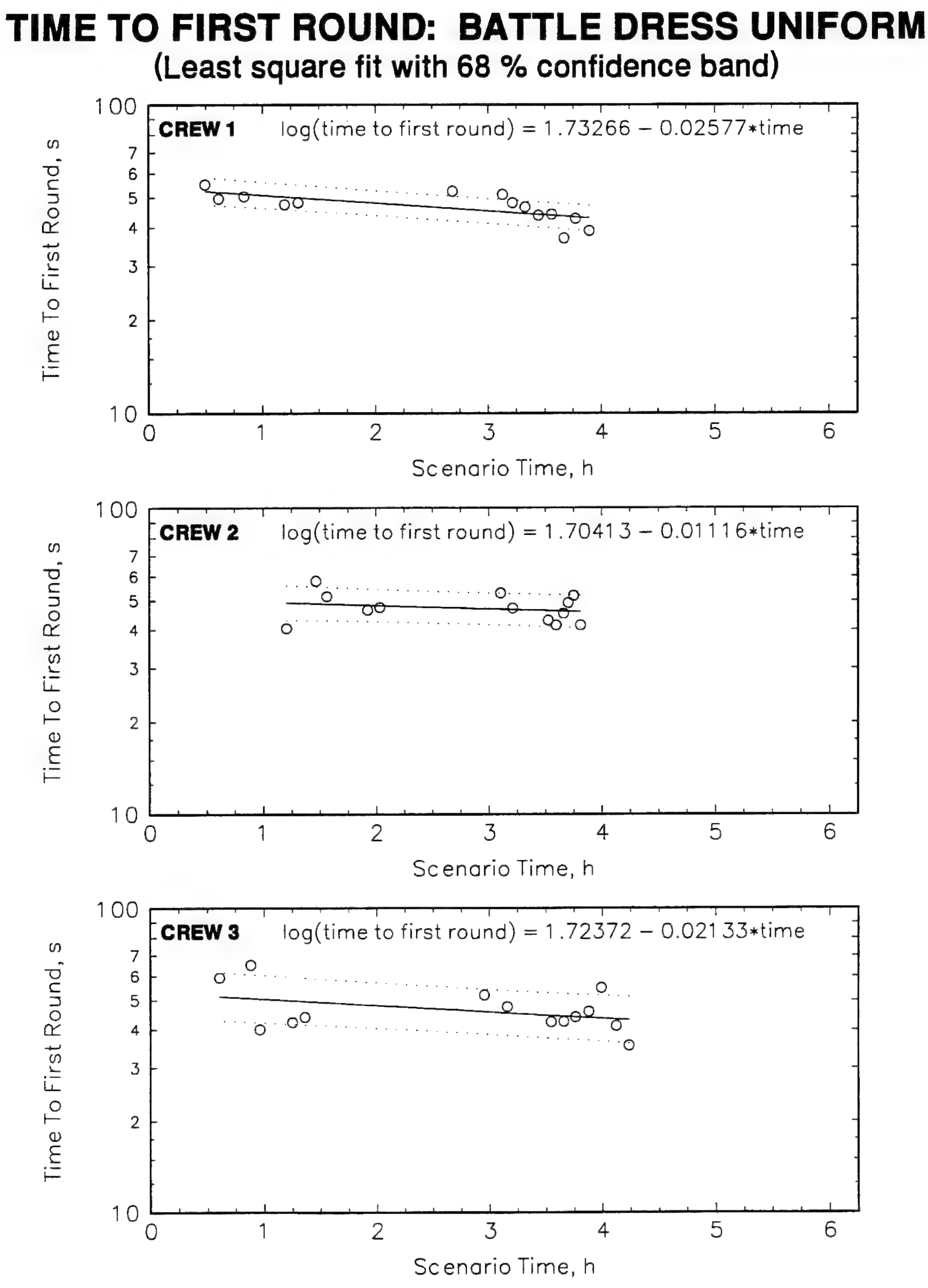

Figure 5-1. TTFR for normal fire missions in BDU. Solid line is linear regression of the logarithmic data with dotted lines indicating 68% confidence band.

The solid lines plotted in Figure 5-1 show the linear regressions of log(TTFR) versus scenario time for each of the crews. The dotted lines on either side of a regression line define the 68% confidence band for the data. Under the assumption that the logarithm of TTFR follows a normal distribution, another single measurement of TTFR has a 68% chance of falling between the dotted lines. The regression line and confidence bands were calculated with a subroutine of AXUM™ which is the graphics software package used to produce all data plots in this report.

The first three columns of Table 5-1 present a statistical summary of the three regression analyses of Figure 5-1 as generated by AXUM. Please note that regression analyses for all data in this report were performed with scenario times and task times both expressed in seconds. The values in all statistical summary tables reflect these units. For plotting in the Figures, on the other hand, scenario time was converted to hours and the linear formula included in each Figure reflects this conversion. For all three crews, the regression lines of Figure 5-1 slope downward with increasing time indicating that all three crews perform faster as the day goes on. Trends of this sort are usually due to a practice (or learning) effect. The data shows that any slowing from fatigue for this task sequence in battle dress uniform is more than compensated for by the practice effect.

To judge the significance of the downward slope, we need to examine the standard error of the slopes listed in Table 5-1. The *t-ratio* associated with each slope is the value of the slope divided by the standard error of the slope. The *t-ratio* is the measure of how many standard deviations the slope differs from zero. Table 5-1 also lists *prob t* for the slope according to Student's t-test. This value is the probability of obtaining a value at least as large as the observed slope from a regression analysis of a series of random trials when the mean task time is not changing, that is when the true slope is zero. The *prob t* values for Crews 2 and 3 are both larger than 5%, indicating a reasonable chance that each set of data by itself is consistent with zero slope. (Both of these data sets were used in Section 3 as data sets with stable means for the purpose of statistical characterization of the data.)

On the other hand, the slope for Crew 1 has a probability of less than 1% of being zero, indicating a significant improvement with repetition. Since all three crews show an improvement, it is likely that the data if aggregated would show a more significant slope than any one data set alone. The analysis of variance (ANOVA) test may be applied to the three data sets to test the hypothesis that there is no statistically significant difference among the three crews. If this hypothesis is justified, then the three data sets may be aggregated without reservation.

™AXUM is a registered trademark of TriMetrix, Inc., Seattle, Washington.

Table 5-1. Statistical summary for regression analysis of time to first round (TTFR) in battle dress uniform (BDU) for normal fire missions.

For each crew: log(time to first round) = constant + slope*<mission time>

For *All Crews*: log(time to first round) = constant + slope*<mission number>

	Crew 1	*Crew 2*	*Crew 3*	*All Crews*
Mean of Dependent Variable	1.66796	1.67276	1.66531	1.66858
Number of Observations	14	13	14	41
Total Sum of Squares	0.03119	0.02678	0.06734	0.12569
Residual Sum of Squares	0.01659	0.02528	0.05596	0.09040
Std. Dev. of Estimate	0.03718	0.04794	0.06829	0.04814
R-squared	0.46819	0.05616	0.16898	0.28080
Adjusted R-squared	0.42387	-0.02964	0.09973	0.26236
Degrees of Freedom (df)	12	11	12	39
Number of Ind Vars (K)	2	2	2	2
F(K-1, df)	10.56432	0.65451	2.44008	15.22689
Prob. Value of F	0.00695	0.43565	0.14424	0.00037
Constant	1.73266	1.70413	1.72372	1.72628
Standard error	0.02225	0.04099	0.04161	0.01659
Slope[1]	-7.16e-6	-3.10e-6	-5.92e-6	-0.00605
Standard error	2.20e-6	3.83e-6	3.79e-6	0.00155
t-ratio	-3.25028	-0.80902	-1.56208	-3.90216
prob t	0.00695	0.43565	0.14424	3.66e-4
Correlation Coefficient	-0.68424	-0.23698	-0.41107	-0.52991

[1]Slope for each crew is measured in units of log(seconds) per second. Values quoted in Figures have been converted to log(seconds) per hour. For *All Crews*, the slope is in units of log(seconds) per fire mission.

The ANOVA test uses the measured TTFR's for each crew as a random sample of measurements without regard to the scenario time at which they occurred. Table 5-2 presents results of the ANOVA test as provided by the AXUM software. The test shows no statistically significant difference among the three data sets. According to the ANOVA, the probability (*Prob. Value of F*) of differences larger than or equal to the observed variations among the three crews is 94% even if all trials were done by the same crew.

The ANOVA test indicates that the TTFR measurements in BDU may be aggregated without further qualification. Since the data seem to show a practice effect, the aggregated data is plotted versus repetition number. This choice avoids the logical contradiction of having a regression line versus scenario time that predicts a steady improvement in TTFR with practice during the resupply interval when no fire missions are being conducted.

Table 5-2. Analysis of variance (ANOVA) for TTFR for normal fire missions of the 3 crews in BDU.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.00038	2	0.00019
Error	0.12531	38	0.00330

Mean of Dep. Var	1.66858
Number of Obs	41
Total Sum of Squares	0.12569
Residual Sum of Squares	0.12531
Std. Dev. of Estimate	0.05742
R-squared	0.00304
Adjusted R-squared	-0.04943
Degrees of Freedom (df)	38
Number of Ind Vars (K)	3
F(K-1, df)	0.05801
Prob. Value of F	0.94372

Since the same basic operations are performed once at the start of each fire mission for all mission types, the fire mission number is assumed to be the appropriate repetition number for time to first round regardless of mission type. It is also assumed that the repetition number does not carry over from day to day but rather starts with 1 each day. As such, it may be more proper to refer to the improving performance as a daily *warm-up* effect rather than a practice effect.

Figure 5-2 shows the aggregated BDU data for TTFR plotted versus fire mission number. The plot includes a regression line whose statistical parameters are listed in Table 5-1 under *All Crews*. The aggregated data has a definite, well-determined slope. *Prob t* indicates a chance of less than 0.001 that a practice or warm-up effect as large or larger than the one observed would occur at random.

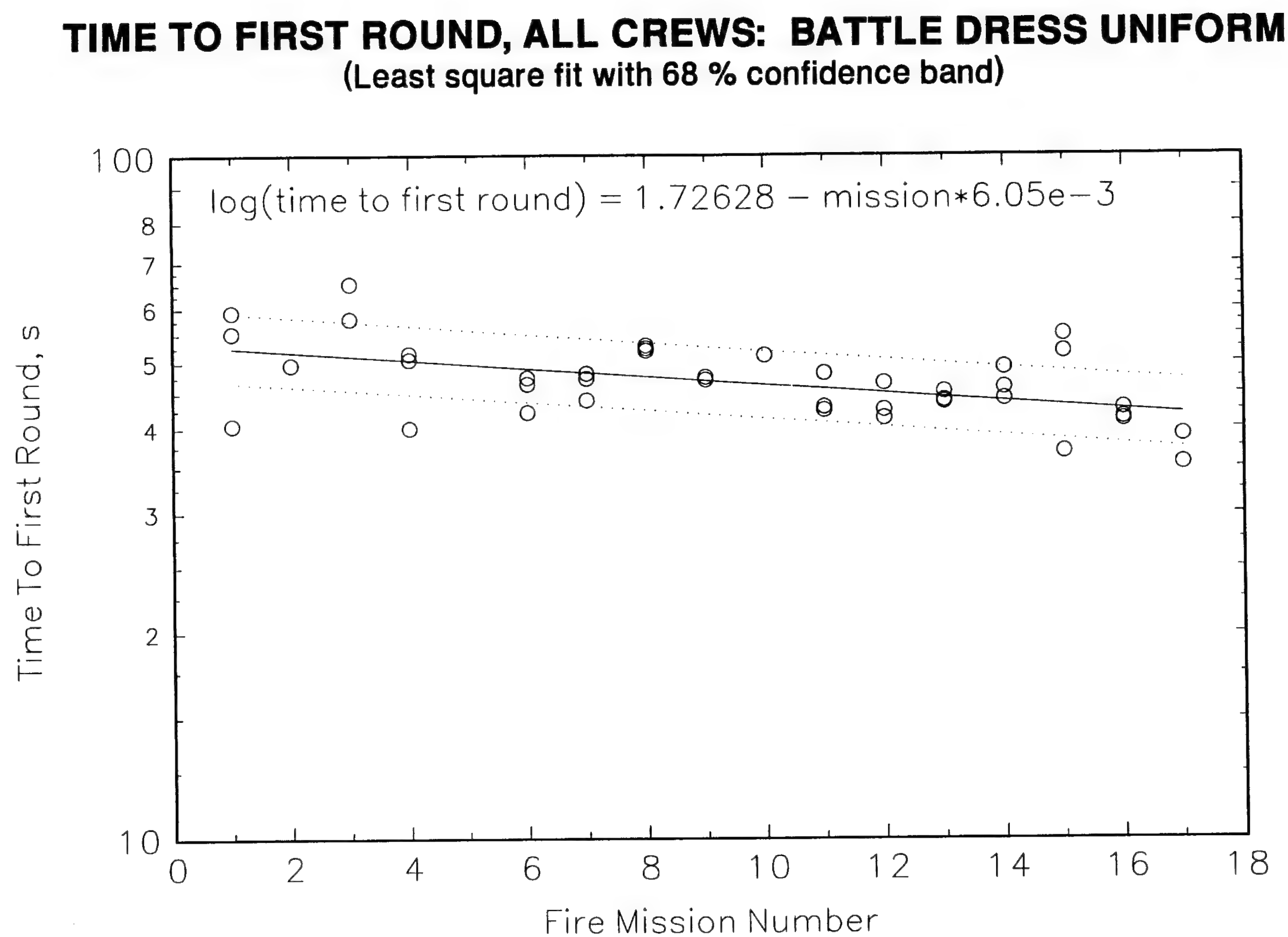

Figure 5-2. Aggregated data for TTFR of normal fire missions in BDU.

Table 5-3 lists the expected value of TTFR for each repetition number from 1 to 17 according to the regression line of Figure 5-2. The standard deviation of the logarithm of TTFR from the linear regression varies only slightly with fire mission number. A constant value of 0.05 is a good approximation. A linear formula using this value appears at the bottom of Table 5-3. The table also lists the standard deviation as a *relative error*. For a relative error of 12%, the time in seconds should be multiplied and divided by 1.12 to get the upper and lower limits, respectively, of the 68% confidence band. The resulting asymmetric limits on a linear plot come from the assumption that the data is log normally distributed. Equal width confidence limits on the logarithm of TTFR transform to asymmetric limits on TTFR in seconds. This asymmetry is desirable in that it avoids lower confidence bounds that extend to negative times.

Table 5-3. Expected time to first round for normal fire missions with crew in BDU listed by fire mission number.

Mission Number	*Log t(sec)*	*Std Dev of Log t*	*t (sec)*	*Relative Error (%)*	*Standard Error of Mean (%)*
1	1.72022	0.05114	52.50	12.4	2.89
2	1.71417	0.05075	51.78	12.3	2.87
3	1.70812	0.05041	51.06	12.3	2.85
4	1.70207	0.05011	50.35	12.2	2.83
5	1.69602	0.04986	49.66	12.1	2.82
6	1.68997	0.04966	48.97	12.1	2.81
7	1.68392	0.04951	48.29	12.0	2.80
8	1.67787	0.04941	47.62	12.0	2.79
9	1.67182	0.04936	46.97	12.0	2.79
10	1.66577	0.04936	46.32	12.0	2.79
11	1.65972	0.04940	45.67	12.0	2.79
12	1.65367	0.04950	45.04	12.0	2.80
13	1.64762	0.04965	44.42	12.1	2.81
14	1.64157	0.04985	43.81	12.1	2.82
15	1.63552	0.05009	43.20	12.2	2.83
16	1.62947	0.05038	42.60	12.3	2.85
17	1.62342	0.05072	42.01	12.3	2.87

$$\log(t) = [1.726 - (6.05 \times 10^{-3})N] \pm 0.05 \qquad N \leq 20$$

For estimating the next fire mission after already firing N-1 missions.
Not valid for greater than about 20 fire missions.

Table 5-3 also lists the standard error of the mean for the regression line of TTFR expressed as a relative error. This value indicates the uncertainty in the central value of TTFR versus daily fire mission number.

Since it is clear that the mean value of TTFR cannot keep decreasing after an indefinite number of repetitions, the regression line should not be extrapolated beyond about 20 fire missions. Sooner or later, the crew will reach peak performance and then deteriorate from fatigue. Data is not available from this effort to determine after how many repetitions TTFR would level out and then begin to increase.

5.1.2 MOPP4 With Standard Crew Positions.

Each crew attempted one scenario in MOPP4 with standard crew positions. Figure 5-3 presents the resulting TTFR's plotted versus scenario. Within a few minutes, time-in-MOPP4 is equivalent to scenario time. Once again, linear regressions are performed for each of the crews. The lines and confidence bands are plotted in Figure 5-3 and statistical summaries are listed in Table 5-4.

The mean TTFR's for the three crews range from 63 to 78 and appear to be increasing with time-in-MOPP4. For comparison, the baseline BDU value as shown in Table 5-3 is around 50 s for comparable mission numbers and is decreasing.

For all three crews, the regression line has a positive slope, indicating worsening performance with time-in-MOPP4. Table 5-4 shows, however, that the slopes for Crews 1 and 3 are not statistically significant, having probabilities of 71% and 35%, respectively, of being consistent with zero. Crew 2 has a significant slope at the 5% level of confidence, but the small number of points and the unusually small standard deviation of the estimate causes suspicion of a statistical fluke. Thus, one might consider the possibility that the measured TTFR's with the crews in MOPP4 with standard crew positions are consistent with a constant level of performance.

On the other hand, the ANOVA test, summarized in Table 5-5, indicates that the data from the three crews may be aggregated. The aggregation would likely show a significant positive slope. Moreover, because of increasing heat stress, none of the crews was able to complete its scenario, so it is unlikely that performance was unaffected. In particular, Crew 2, with the highest slope, completed the fewest fire missions. Finally, it is assumed that in the absence of heat stress and fatigue, performance in MOPP gear should improve with time, showing a practice or warm-up effect similar to performance in BDU. Thus, the putative positive slope of the MOPP4 task times should be compared with the negative slope of the BDU data rather than with zero slope. These factors argue for a significantly declining performance with time-in-MOPP4.

Before any further comparison of BDU and MOPP4 data, the MOPP4 data with rotating crew positions should be examined.

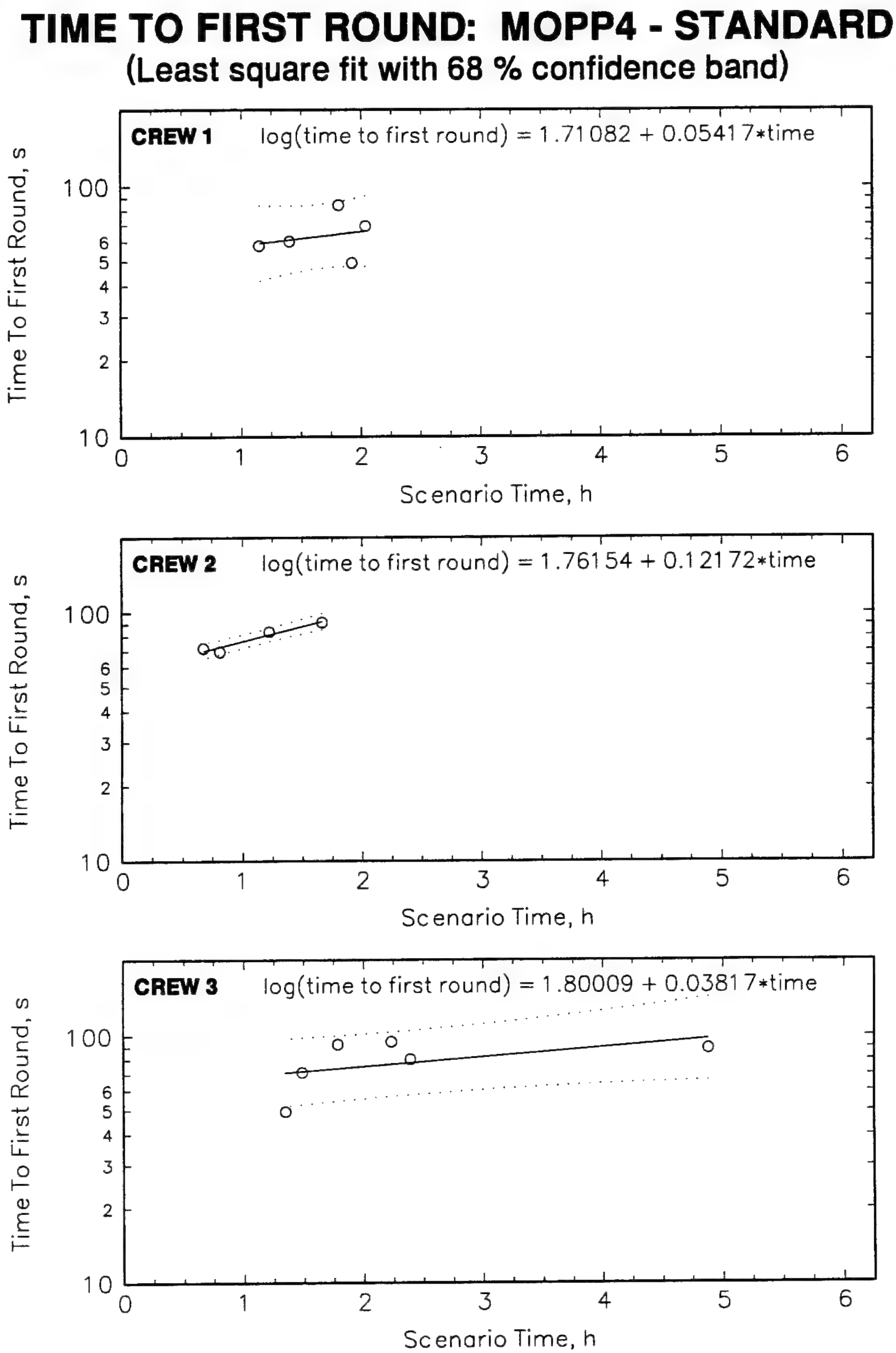

Figure 5-3. TTFR for normal fire missions with crew in MOPP4 with standard crew positions (MOPP4-S).

Table 5-4. Statistical summary for TTFR for normal fire missions in MOPP4 with standard crew (MOPP4-S).

log(time to first round) = constant + slope*<mission time>

	Crew 1	*Crew 2*	*Crew 3*
Mean of Dependent Variable	1.80085	1.89477	1.88988
Number of Observations	5	4	6
Total Sum of Squares	0.03057	0.00954	0.05673
Residual Sum of Squares	0.02891	0.00067	0.04436
Std. Dev. of Estimate	0.09816	0.01833	0.10531
R-squared	0.05421	0.92950	0.21793
Adjusted R-squared	-0.26105	0.89425	0.02242
Degrees of Freedom (df)	3	2	4
Number of Ind Vars (K)	2	2	2
F(K-1, df)	0.17196	26.36878	1.11465
Prob. Value of F	0.70625	0.03589	0.35062
Constant	1.71082	1.76154	1.80009
Standard error	0.22152	0.02752	0.09530
Slope[1]	1.51e-5	3.38e-5	1.06e-5
Standard error	3.63e-5	6.58e-6	1.00e-5
t-ratio	0.41468	5.13505	1.05577
prob t	0.70625	0.03589	0.35062
Correlation Coefficient	0.23283	0.96411	0.46883

[1]Slope for each crew is measured in units of log(seconds) per second. Values quoted in Figures have been converted to log(seconds) per hour.

Table 5-5. ANOVA for normal fire missions with crews in MOPP4-S (Figure 5-3).

	Sum Sq	*DF*	*Mean Sq*
Crew	0.02765	2	0.01382
Error	0.09683	12	0.00807

Mean of Dep. Var	1.86151
Number of Obs	15
Total Sum of Squares	0.12448
Residual Sum of Squares	0.09683
Std. Dev. of Estimate	0.08983
R-squared	0.22213
Adjusted R-squared	-0.09248
Degrees of Freedom (df)	12
Number of Ind Vars (K)	3
F(K-1, df)	1.71332
Prob. Value of F	0.22154

5.1.3 MOPP4 With Rotating Crew Positions.

Because of technical difficulties with instrumentation on the first day of the exercise with Crew 1, only Crews 2 and 3 attempted a scenario in MOPP4 with rotating crew positions (MOPP4-R). Figure 5-4 presents the resulting TTFR's versus scenario time. Regression lines are plotted in Figure 5-4. Table 5-6 summarizes statistical information for the regression analyses.

The most striking thing about the MOPP4-R data is that Crew 2 was able to complete its 17 round scenario. This fact is of the utmost operational significance and needs to be evaluated in more detail based on the procedures used by the crew and the meteorological conditions. For the purposes of this report, the Crew 2 data provides an extended time series supporting a regression analysis with the same accuracy as the baseline data. Table 5-6 shows that the Crew 2 data has a positive slope with only a 1.5% chance of being consistent with no slope and a much less chance of agreeing with the negative slopes of the baseline BDU data of Table 5-1. The increasing TTFR's must be interpreted in terms of both accumulating heat stress and loss of crew members since Crew 2 was down to 7 crew members by the end of the scenario.

The regression line for Crew 3 is consistent with zero slope but has a three fold larger standard error than that of Crew 2. An ANOVA test shown in Table 5-7 shows that the two sets of data have consistent means and could be aggregated. The larger standard error of the Crew 3 slope stems mainly from the unusually long TTFR for the second data point. Further analysis of this data should include examination of such outliers.

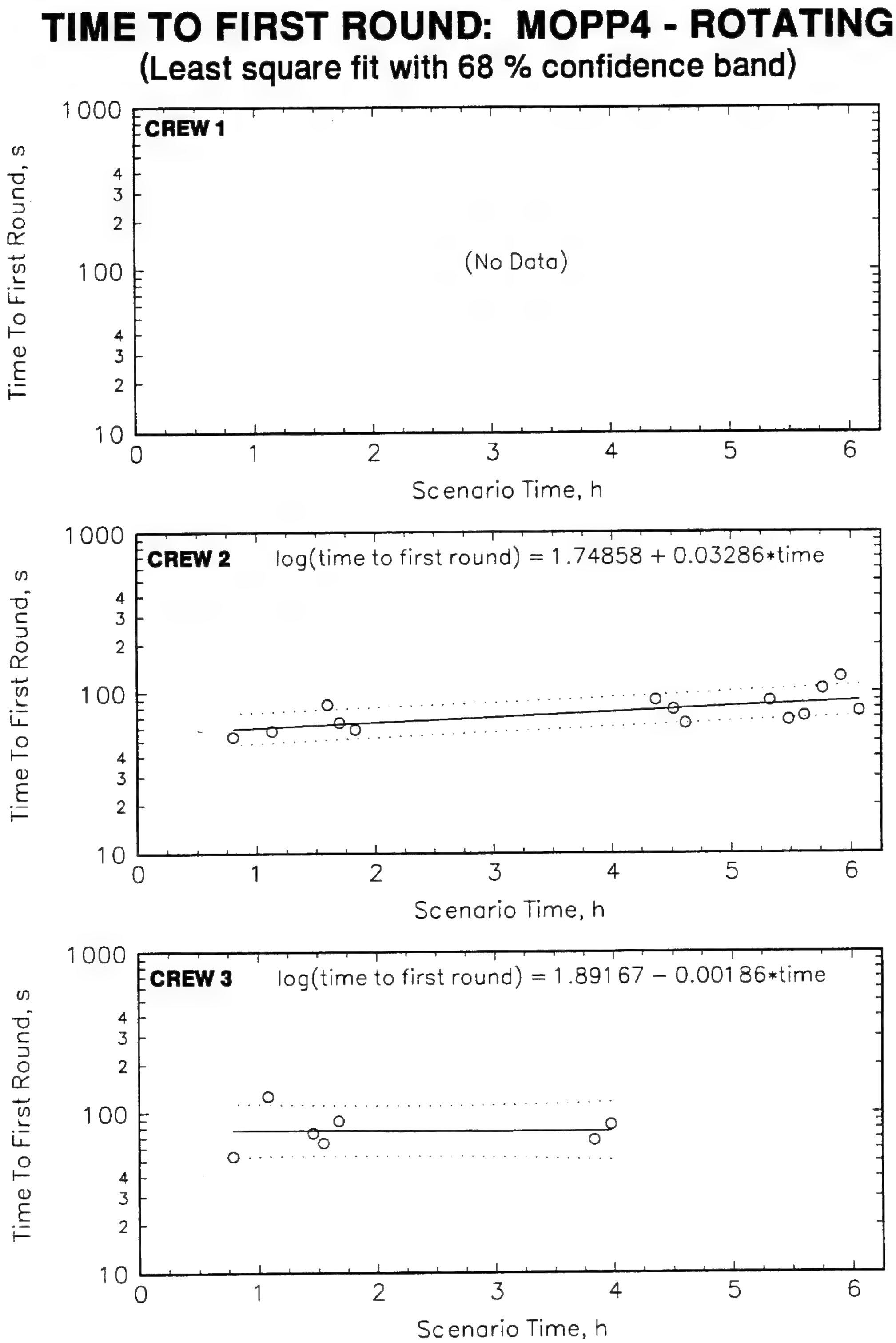

Figure 5-4. TTFR for normal fire missions with crew in MOPP4 with rotating crew positions (MOPP4-R).

Table 5-6. Statistical summary for TTFR for normal fire missions with crew in MOPP4 with rotating crew positions (MOPP4-R).

log(time to first round) = constant + slope*<mission time>

	Crew 1	*Crew 2*	*Crew 3*
Mean of Dependent Variable	No Data	1.87696	1.88785
Number of Observations		14	7
Total Sum of Squares		0.14081	0.08757
Residual Sum of Squares		0.08407	0.08754
Std. Dev. of Estimate		0.08370	0.13231
R-squared		0.40300	0.00040
Adjusted R-squared		0.35324	-0.19952
Degrees of Freedom (df)		12	5
Number of Ind Vars (K)		2	2
F(K-1, df)		8.10034	0.00202
Prob. Value of F		0.01473	0.96592
Constant		1.74858	1.89167
Standard error		0.05035	0.09858
Slope[1]		9.13e-6	-5.17e-7
Standard error		3.21e-6	1.15e-5
t-ratio		2.84611	-0.04490
prob t		0.01473	0.96592
Correlation Coefficient		0.63482	-0.02008

[1]Slope for each crew is measured in units of log(seconds) per second. Values quoted in Figures have been converted to log(seconds) per hour.

Table 5-7. ANOVA for TTFR for normal fire missions with crews in MOPP4-R. (Figure 5-4).

	Sum Sq	*DF*	*Mean Sq*
Crew	0.00055	1	0.00055
Error	0.22838	19	0.01202

Mean of Dep. Var	1.88059
Number of Obs	21
Total Sum of Squares	0.22894
Residual Sum of Squares	0.22838
Std. Dev. of Estimate	0.10964
R-squared	0.00242
Adjusted R-squared	-0.05009
Degrees of Freedom (df)	19
Number of Ind Vars (K)	2
F(K-1, df)	0.04603
Prob. Value of F	0.83241

5.1.4 Discussion of TTFR Performance for Normal Fire Missions.

The baseline BDU data for time to first round shows a significant practice or warm-up effect. On a daily basis after 17 fire missions, the average TTFR improves from 52 to 42 seconds. Table 5-3 includes a linear formula for the logarithm (to the base 10) of the mean TTFR versus fire mission number and includes a standard deviation of .05 for the logarithm. For a Monte Carlo simulation in an engagement model, the logarithm of TTFR for a given fire mission number should be drawn at random from the appropriate normal distribution and then converted to a time in seconds. The formula should not be used for more than 20 fire missions since it is not known after how many fire missions performance in battle dress uniform becomes steady and then deteriorates. The quoted standard deviation is from variation of crew performance during this exercise and has negligible contribution from measurement error.

Fire mission scenarios in MOPP4 indicate that a regimented rotation of crew positions to distribute thermal-related work load among crew members increases the number of fire missions that can be accomplished with moderate heat stress. On the other hand, performance levels while still in action were not significantly different between rotating and standard crew positions for this exercise. Table 5-8 presents an analysis of variance for all five scenarios in which the crews operated in MOPP4. With high probability (57%), the data sets are equivalent on a time-independent basis and may be aggregated for further analysis. The logarithm of TTFR for the five cases has a mean of 1.87 and a standard deviation of 0.10 corresponding to a TTFR of 74 seconds.

Table 5-8. ANOVA for TTFR for normal fire missions for all scenarios with crew in MOPP4 (MOPP4-S and MOPP4-R).

	Sum Sq	*DF*	*Mean Sq*
Crew	0.03139	4	0.00785
Error	0.32521	31	0.01049

Mean of Dep. Var	1.87264
Number of Obs	36
Total Sum of Squares	0.35660
Residual Sum of Squares	0.32521
Std. Dev. of Estimate	0.10242
R-squared	0.08803
Adjusted R-squared	-0.02965
Degrees of Freedom (df)	31
Number of Ind Vars (K)	5
F(K-1, df)	0.74804
Prob. Value of F	0.56683

The performance degradation averaged over all scenario times in MOPP4 relative to BDU is then 30% to 40% depending on fire mission number. Analysis accounting for the variation of mean TTFR with time-in-MOPP4 will show wider variation of degradation.

5.2 HIGH ANGLE FIRE MISSIONS.

This subsection presents time to first round (TTFR) data for high angle (HA) fire missions, that is, those with elevation angle more than 1000 milliradians. Each HA fire mission consisted of 5 rounds delivered to a single aim point. For these missions, the barrel could not be elevated to the final angle until after the powder and projectile were loaded. The same explanations and caveats apply to the HA missions as to normal missions. Differences are due mainly to fewer fire missions; each scenario had only two HA missions, both before resupply. Because of the limited interval of scenario time covered by the high angle missions, TTFR is plotted only against fire mission number.

Figure 5-5 presents TTFR versus fire mission number for the crews in battle dress uniform. Because each crew fired only two HA missions, the data is analyzed as a group. The dashed line sloping upwards in Figure 5-5 is the linear regression line. Note that this line has a slight upward curvature since the regression was done on the logarithm of TTFR as explained earlier. Table 5-9 shows the statistical summary of this regression analysis. The slope is consistent with zero since the standard error of the slope is twice as big as the slope itself. The regression

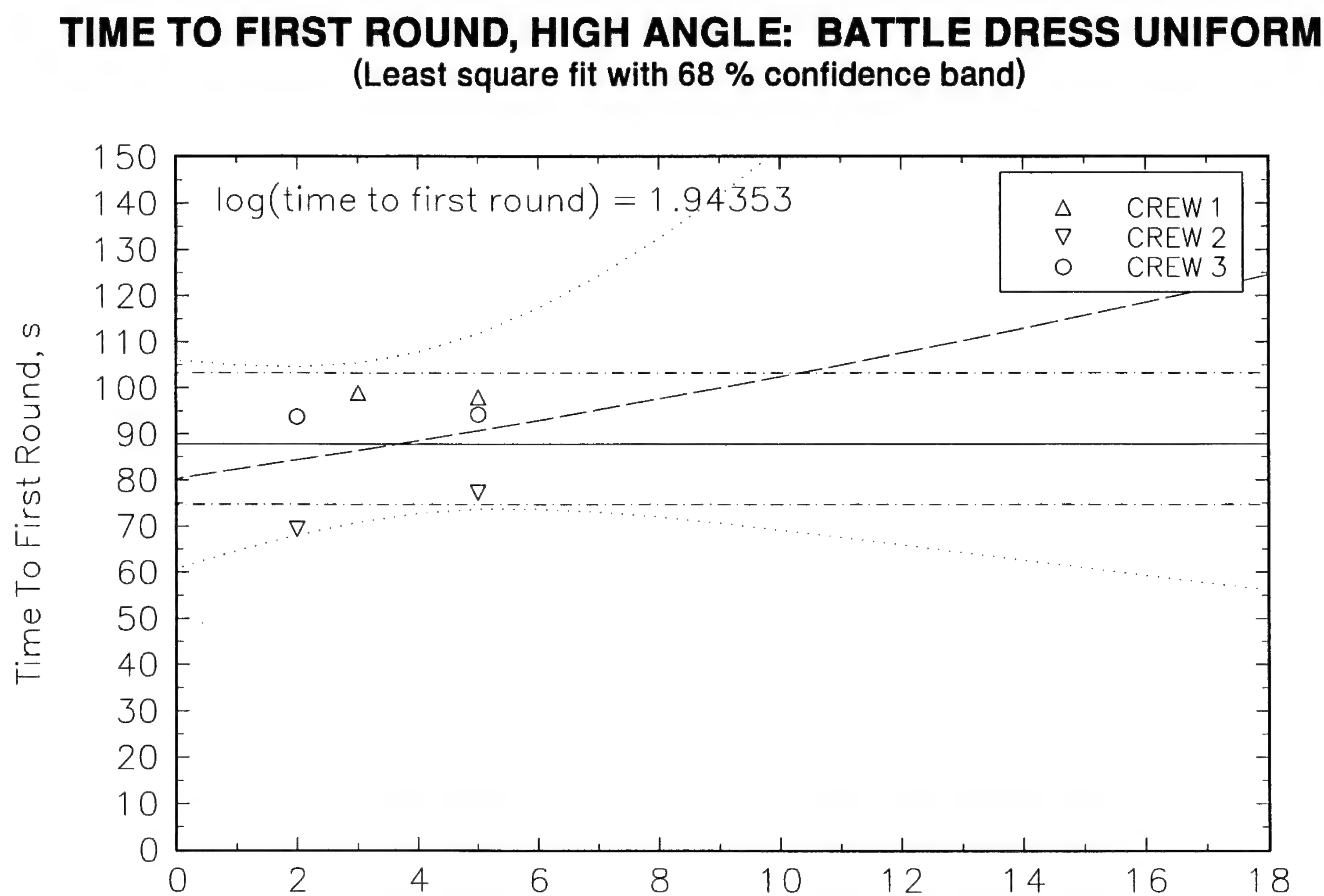

Figure 5-5. TTFR for high angle missions with crew in BDU. The dashed line shows a logarithmic linear regression and the solid line shows the mean of the data.

Table 5-9. Statistical summary for TTFR for high angle missions with crew in BDU.

log(time to first round) = constant + slope*<mission number>

	All Crews
Mean of Dependent Variable	1.94353
Number of Observations	6
Total Sum of Squares	0.02031
Residual Sum of Squares	0.01904
Std. Dev. of Estimate	0.06900
R-squared	0.06235
Adjusted R-squared	-0.17206
Degrees of Freedom (df)	4
Number of Ind Vars (K)	2
F(K-1, df)	0.26600
Prob. Value of F	0.63322
Constant	1.90477
Standard error	0.08026
Slope[1]	0.01057
Standard error	0.02050
t-ratio	0.51575
prob t	0.63322
Correlation Coefficient	0.24971

[1]Slope is measured in units of log (seconds) per mission number.

analysis shows that there is not enough data and the data does not cover enough fire missions to ascertain whether the mean TTFR changes as a function of time or mission number. Table 5-10 provides statistical parameters of the TTFR data without regard to mission number. A solid line with no slope in Figure 5-5 plots the corresponding mean value and confidence band. The mean of log(TTFR) is 1.944 with a standard deviation of .064. The corresponding value of TTFR is 88 seconds.

Figure 5-6 presents TTFR versus fire mission number for MOPP4-S and MOPP4-R. Regression analyses were not done since the data are not sufficiently correlated to determine a slope. Table 5-11 provides statistical parameters for each set of TTFR data. The MOPP4-S data has a mean TTFR of 138 s while the MOPP4-R data has a mean of 104 s. Two factors contribute to the difference. First, the MOPP4-S data has one outlier near 200 s for Crew 1 which did not do a scenario at MOPP4-R. Second, since the MOPP4-R data was the second scenario in MOPP4 for both Crews 2 and 3, there is a possibility for a learning effect. In any case, the data is consistent with a 30% or 40% degradation in MOPP4 relative to BDU baseline just as in the case of normal fire missions.

5.3 ZONE AND SWEEP FIRE MISSIONS.

This subsection presents time to first (TTFR) round data for zone and sweep (ZS) fire missions. A ZS fire mission consists of 25 rounds with the aim point adjusted on each round to produce a 5 x 5 grid for the lay down pattern. Even less data is available for this mission type than for the high angle type. Each scenario had only one ZS fire mission and it occurred after resupply. Only two attempted scenarios in MOPP4 reached the ZS mission, one for Crew 2 (MOPP4-R) and one for Crew 3 (MOPP4-S). Figure 5-7 shows plots of TTFR versus fire mission number for the BDU data and the aggregated MOPP4 data. Table 5-12 summarizes the corresponding statistical parameters. The data indicates about 32% degradation in MOPP4 relative to BDU.

Table 5-10. Statistical parameters for log(TTFR) for high angle fire missions with crew in BDU ignoring mission number.

Minimum	1.84086
Maximum	1.99524
Sum	11.66116
Mean	1.94353
Median	1.97296
Variance	0.00406
Std. Deviation	0.06373
Standard Error	0.02602
Valid Observations	6
Total Observations	6
68 % Confidence Interval	0.02872

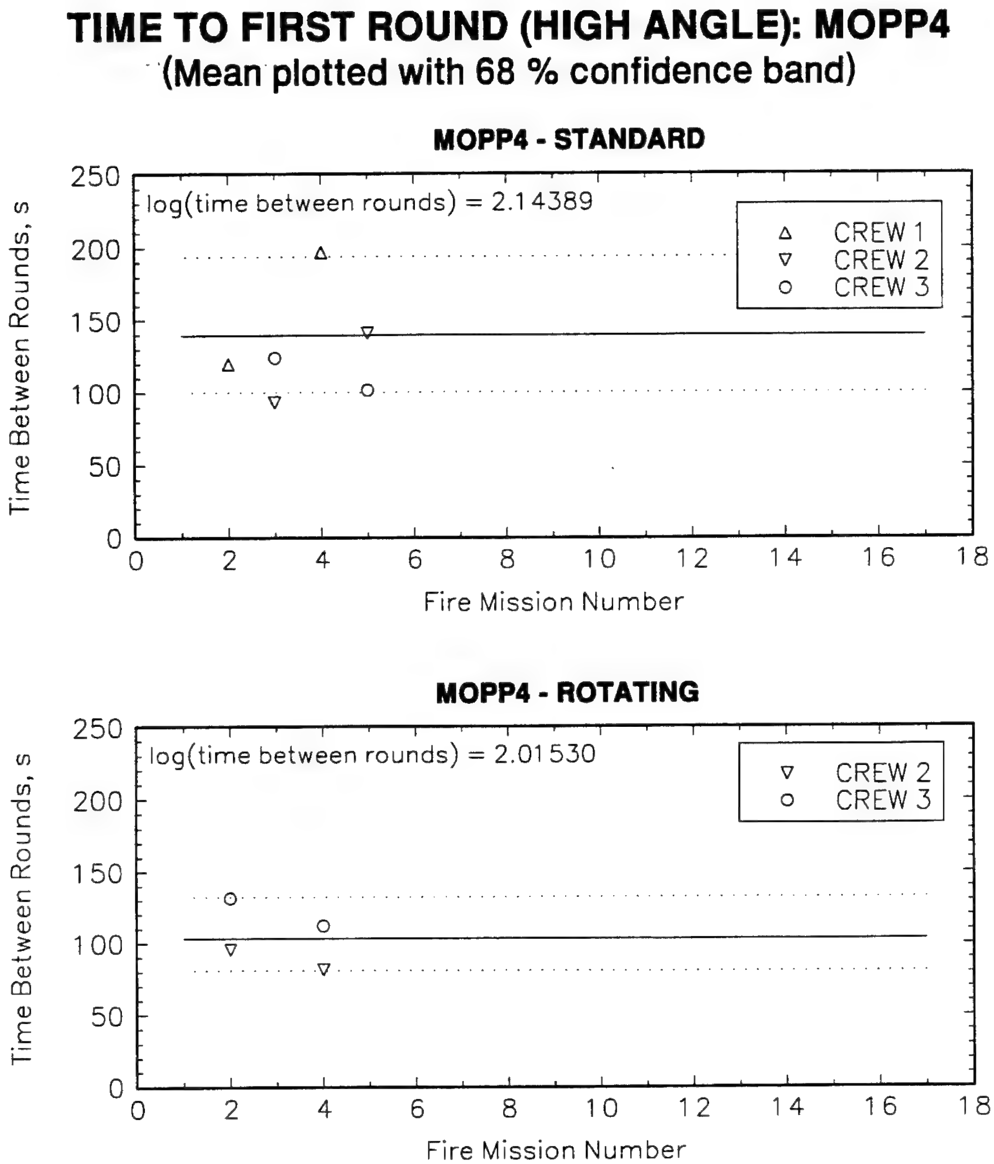

Figure 5-6. TTFR for high angle missions with the crews at MOPP4-S and MOPP4-R.

Table 5-11. Statistical parameters of log(TTFR) for high angle missions with crews in MOPP4-S and MOPP4-R.

	Standard	*Rotating*
Minimum	1.96960	1.91137
Maximum	2.29374	2.11899
Sum	12.86333	8.06120
Mean	2.14389	2.01530
Median	2.11368	2.01542
Variance	0.01675	0.00800
Std. Deviation	0.12943	0.08943
Stdandard Error	0.05284	0.04471
Valid Observations	6	4
Total Obsservations	6	4
68 % Confidence Interval	0.05832	0.05316

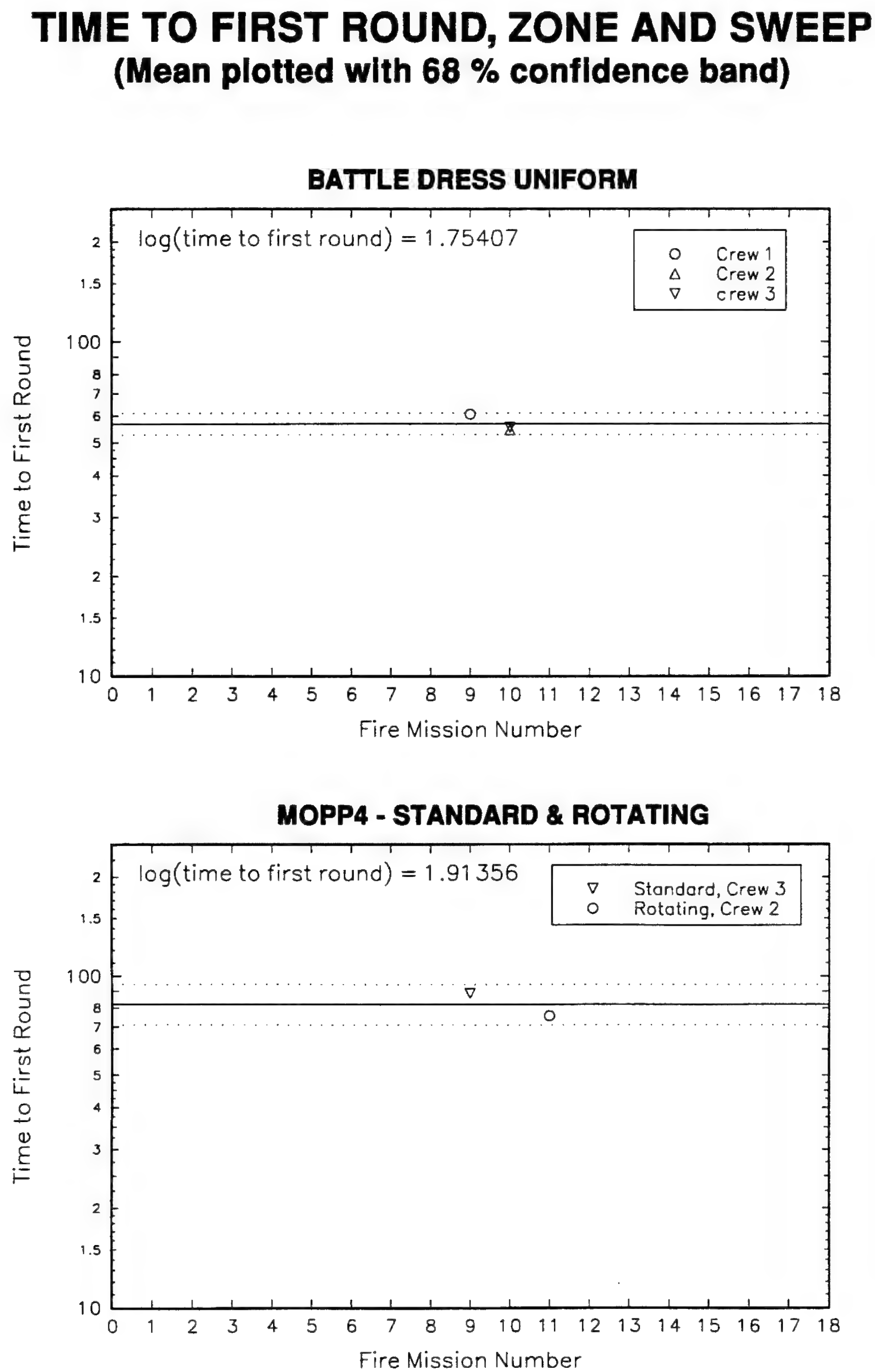

Figure 5-7. TTFR for zone and sweep missions with crew in BDU and in MOPP4. Mean values indicated by solid lines according to Table 5-12.

Table 5-12. Statistical parameters of log(TTFR) for zone and sweep missions with crews in BDU and with MOPP4-S and MOPP4-R aggregated.

log(time to first round) = mean

	BDU	*MOPP4*
Minimum	1.73592	1.87955
Maximum	1.78247	1.94758
Sum	5.26221	3.82713
Mean	1.75407	1.91356
Median	1.74381	1.91356
Variance	0.00062	0.00231
Std. Deviation	0.02491	0.04810
Stdandard Error	0.01438	0.03401
Valid Observations	3	2
Total Obsservations	3	2
68 % Confidence Interval	0.01887	0.06187

SECTION 6
TIME BETWEEN ROUNDS

Except for an occasional safety check for a primer misfire or range safety problem, the calculation of time between rounds (TBR) requires only the measured firing times described in Section 3. For an N round mission, there are N-1 measured TBR intervals. Typical TBR's range from 20 seconds for normal fire missions to more than a minute for high angle missions, so the measurement uncertainty of less than 0.1 seconds in the firing times is entirely negligible. When a safety check occurred between two rounds, the time of the safety check is subtracted from TBR. In this case, the root mean square uncertainty may be a second or two.

The scenarios for this exercise had built in wait times of several minutes between fire missions. Since the barrel of the howitzer could cool during this wait time, no restrictions on rate of fire because of barrel temperature were in effect during fire missions.

Since variation of performance with time is of central interest, the reduced data is expressed as time between rounds rather than as rate of fire, the inverse of TBR. With this choice, the variation of TBR over the course of a single, long fire mission can be examined. Furthermore, statistical analysis of the data is more direct since the time intervals tend to be log normally distributed as discussed in Section 3. Final results may be converted to rates of fire.

The following subsections present time-between-rounds data for the three types of fire missions, 1) normal, 2) high angle, and 3) zone and sweep. For each mission type, TBR is reported for three conditions: battle dress uniform (BDU), MOPP4 with standard crew positions (MOPP4-S), and MOPP4 with regimented rotation of positions (MOPP4-R). All fire missions are *fire-for-effect* missions. The presentation of the data follows the same format used for time to first round in Section 5.

6.1 NORMAL FIRE MISSIONS.

This subsection presents the TBR data for normal fire missions, that is, those with elevation angle less than 1000 milliradians and with 3 to 6 rounds fired at a single aim point.

6.1.1 Battle Dress Uniform.

As explained in Section 2, only the second day of BDU data for Crew 1 is being analyzed. Therefore, we have one day of BDU data for each crew. Figure 6-1 presents the TBR data for the normal missions for each crew separately, plotted versus scenario time. Once again, all three crews show a negative slope to their regression lines, suggestive of a practice or warm-up effect. Table 6-1 lists the statistical summaries for the regression analyses. Only Crew 1 is reasonably consistent with a constant mean value of TBR, about 25 s. It should be noted that the data for Crew 1 is the second BDU scenario for the crew. The other crews had only one chance. Crew 2 operated in BDU for its first scenario and it shows the largest negative slope. Crew 3 operated

TIME BETWEEN ROUNDS: BATTLE DRESS UNIFORM
(Least square fit with 68 % confidence band)

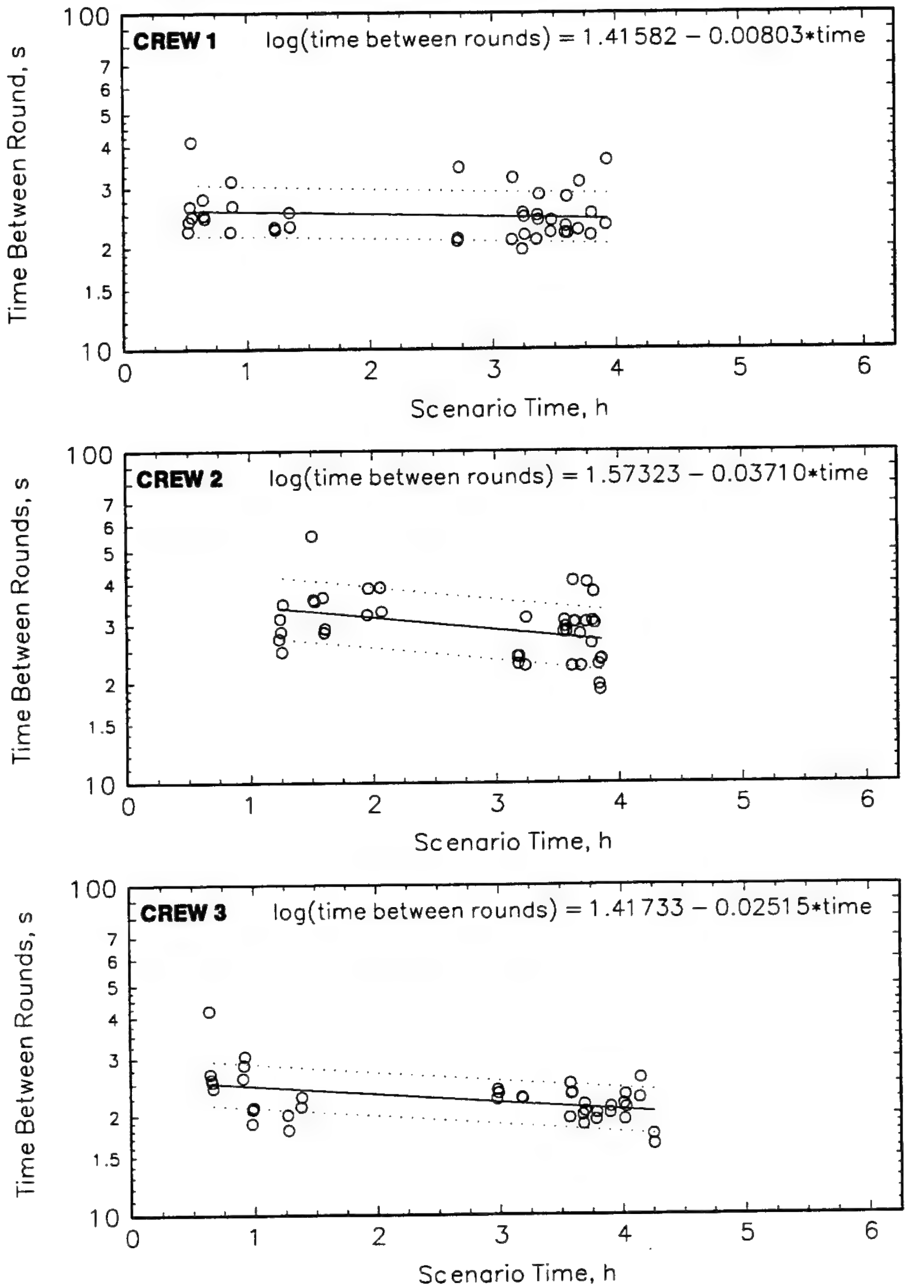

Figure 6-1. Time between rounds (TBR) for normal fire missions in battle dress uniforms (BDU). Solid line is linear regression of the logarithmic data with plotted lines indicating 68 % confidence band.

first in MOPP4-S and second in BDU. The Crew 3 data shows a smaller but still significant negative slope, has the smallest standard deviation of all crews, and approaches an average TBR of 20 s after resupply.

Table 6-1. Statistical summary for regression analyses of time between rounds (TBR) in battle dress uniform (BDU) for normal fire missions.

For *All Crews*: log(time between rounds) = constant + slope*<round number>
For each crew: log(time between rounds) = constant + slope*<mission time>

	Crew 1	*Crew 2*	*Crew 3*	*All Crews*
Mean of Dependent Variable	1.39626	1.46678	1.35010	1.40490
Number of Observations	40	41	40	121
Total Sum of Squares	0.19776	0.36510	0.20457	1.04749
Residual Sum of Squares	0.19348	0.30704	0.15673	0.96803
Std. Dev. of Estimate	0.07135	0.08873	0.06422	0.09019
R-squared	0.02166	0.15902	0.23385	0.07586
Adjusted R-squared	-0.00408	0.13746	0.21369	0.06809
Degrees of Freedom (df)	38	39	38	119
Number of Ind Vars (K)	2	2	2	2
F(K-1, df)	0.84133	7.37470	11.59893	9.76829
Prob. Value of F	0.36480	0.00981	0.00157	0.00223
Constant	1.41582	1.57323	1.41733	1.44562
Standard error	0.02412	0.04158	0.02220	0.01540
Slope[1]	-2.23e-6	-1.03e-5	-6.99e-6	-8.55e-4
Standard error	2.43e-6	3.80e-6	2.05e-6	2.73e-4
t-ratio	-0.91724	-2.71564	-3.40572	-3.12543
prob t	0.36480	0.00981	0.00157	0.00223
Correlation Coefficient	-0.14718	-0.39878	-0.48359	-0.27543

[1]Slope for each crew is measured in units of log(seconds) per second. Values quoted in Figures have been converted to log(seconds) per hour. For *All Crews*, the slope is in units of log(seconds) per round.

An analysis of variance (ANOVA) for the TBR data in BDU is summarized in Table 6-2. The ANOVA confirms that differences in TBR among the three crews as noted in the previous paragraph are statistically significant. Judging from Figure 6-1, the biggest discrepancy is for Crew 2, especially before resupply. The time between rounds before resupply are large

(averaging more than 30 seconds) and badly spread. After resupply, the mean TBR is improved but the standard deviation is still large.

Table 6-2. Analysis of variance (ANOVA) for TBR for normal fire missions of the 3 crews in BDU.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.28006	2	0.14003
Error	0.76743	118	0.00650

Mean of Dep. Var.	1.40490
Number of Obs	121
Total Sum of Squares	1.04749
Residual Sum of Squares	0.76743
Std. Dev. of Estimate	0.08065
R-squared	0.26737
Adjusted R-squared	0.25495
Degrees of Freedom (df)	118
Number of Ind Vars (K)	3
F(K-1, df)	21.53127
Prob. Value of F	0.00000

Crew 2 had one noticeable difficulty during the exercise; the Number One Cannoneer suffered from the *rubber lanyard* effect. He had repeated misfires from pulling the lanyard with insufficient vigor and swiftness. He claimed later that it was his first time firing the M198. Not only did the misfires contribute to increased TBR, but according to notes taken during the exercise by one observer, his sloppy performance seemed to adversely affect the performance of other crew members. This observation could be tested when the detailed task data for the exercise is analyzed. By Wednesday, the Number One Cannoneer had perfected his technique and did not have misfires.

It seems then that a combination of the rubber lanyard effect and the variation of scenario order among the three crews can rationalize the differences in TBR data apparent in Figure 6-1. Interestingly, Figure 5-1 shows that these factors did not have a significant effect on TTFR. The crews performed in a consistent matter on TTFR. Even the small differences among crews for TTFR do not conform to the pattern apparent in the TBR data.

Although the differences among the three crews regarding TBR certainly warrant further consideration, we proceed here to aggregate the data to provide a single characterization of TBR in battle dress uniform. In defense of this aggregation, one might expect similar variations of experience and performance among crews on the battlefield, so it is useful to have a mean and

standard deviation based all of the crews.

Figure 6-2 shows the aggregated TBR data for crews in BDU plotted versus round number. For time between rounds, round number is the appropriate measure of repetition number to account for a practice or warm-up effect. The major gap in this data for normal fire missions corresponds to the 25 round zone and sweep fire mission which began around the 36th round. The two earlier gaps are the high angle missions. For the purpose of representing a repetition number for the TBR task sequence, all three mission types are considered as equivalent.

The *All Crews* column of Table 6-1 provides a statistical summary for the regression line plotted in Figure 6-2. The negative slope corresponding to a practice or warm-up effect is significant, having less than a 1% chance of being this large or larger at random. The differences among the three crews noted before appear as asymmetry in the distribution of data relative to the regression line. It is also apparent from Figure 6-2 that a few of the longer TBR's are outliers caused by some unusual event or misstep by the crew. Nonetheless, the overall characterization of the TBR data by the regression line and associated confidence band is good, reflecting the observed crew-to-crew variability in this exercise. Table 6-3 lists the expected mean and standard deviation for log(TBR) versus round number according to the regression line. The corresponding TBR improves from an early value of 28 seconds to a later value of 24 seconds.

6.1.2 MOPP4 With Standard Crew Positions.

Each crew attempted one scenario in MOPP4 with standard crew positions. Figure 6-3 presents the resulting TBR's plotted versus scenario time. Within a few minutes, scenario time is equivalent to time-in-MOPP4. Once again, we have performed linear regressions for each of the crews. The lines and confidence bands are plotted in Figure 6-3 and statistical summaries are listed in Table 6-4.

The mean TBR's for the three crews range from 37 to 51 seconds and appear to be increasing with time-in-MOPP4. For comparison, the baseline BDU value is around 26 seconds and is decreasing.

For all three crews, the regression line has a positive slope, indicating worsening performance degradation with time-in-MOPP4. Table 6-4 shows that the positive slope is statistically significant for Crews 2 and 3 but not for Crew 1. It is interesting to note that the relatively steep slope for Crew 2 corroborates the corresponding steep slope for the TTFR data from the same scenario as discussed in Section 5.1.2. The rapidly worsening performance seems to portend the early medical halt for this crew.

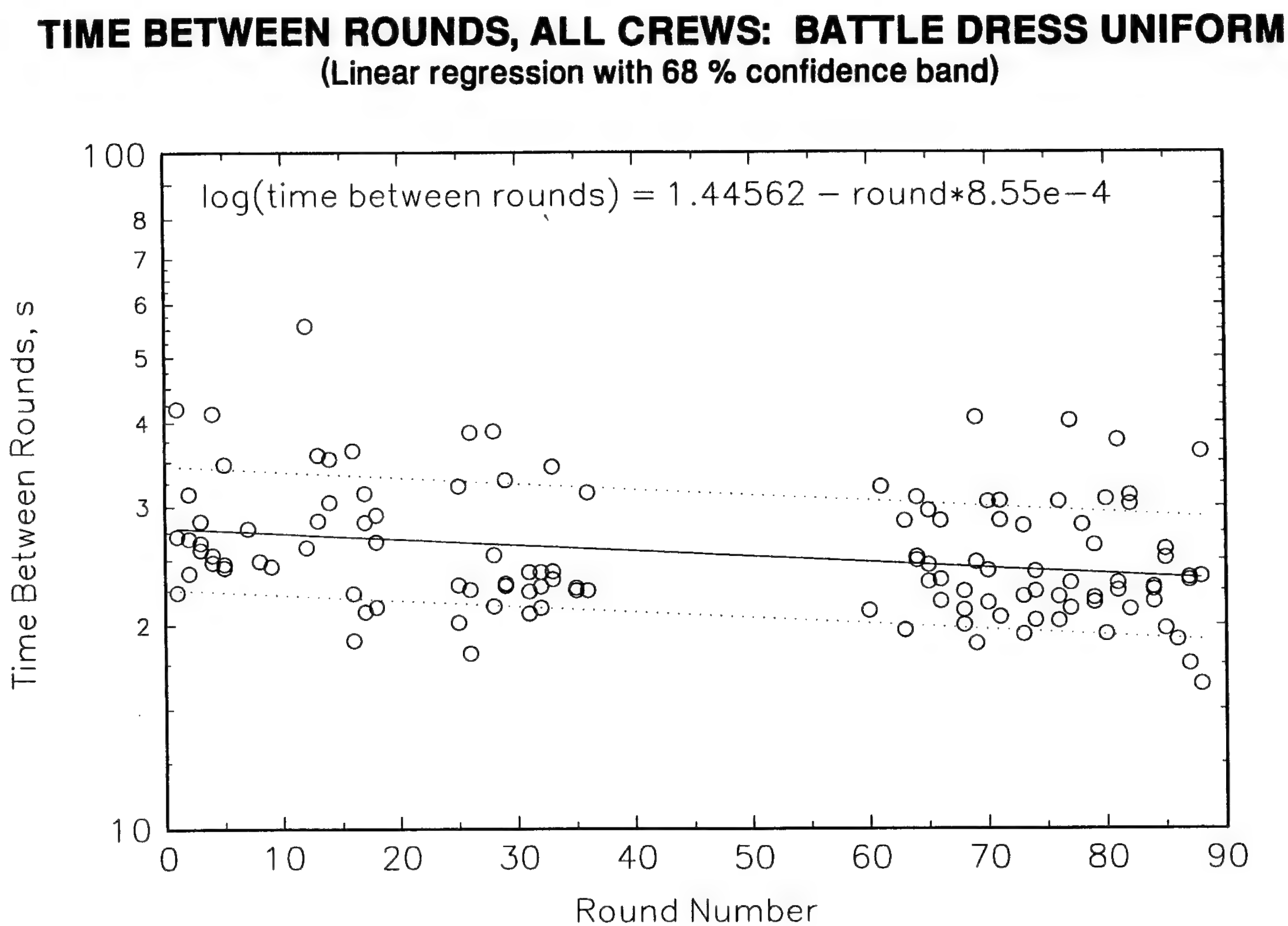

Figure 6-2. Aggregated data for TBR of normal fire missions in BDU.

Table 6-3. Expected TBR for normal fire missions with crew in BDU listed by round number.

Round Number	*Log t*	*Std Dev Log t*	*t (sec)*	*Relative Error (%)*	*Standard Error of Mean (%)*
1	1.44477	0.09183	27.84	23.5	1.94
2	1.44391	0.09179	27.79	23.5	1.93
3	1.44306	0.09175	27.73	23.5	1.93
4	1.44220	0.09172	27.68	23.5	1.93
5	1.44135	0.09168	27.62	23.5	1.93
6	1.44049	0.09165	27.57	23.4	1.93
7	1.43964	0.09161	27.51	23.4	1.93
8	1.43878	0.09158	27.46	23.4	1.93
9	1.43793	0.09155	27.41	23.4	1.93
10	1.43707	0.09152	27.35	23.4	1.93
11	1.43622	0.09148	27.30	23.4	1.93
12	1.43536	0.09145	27.24	23.4	1.93
13	1.43451	0.09143	27.19	23.4	1.93
14	1.43365	0.09140	27.14	23.4	1.93
15	1.43280	0.09137	27.08	23.4	1.93
16	1.43194	0.09134	27.03	23.4	1.93
17	1.43109	0.09132	26.98	23.4	1.92
18	1.43024	0.09129	26.92	23.3	1.92
19	1.42938	0.09127	26.87	23.3	1.92
20	1.42853	0.09125	26.82	23.3	1.92
21	1.42767	0.09122	26.77	23.3	1.92
22	1.42682	0.09120	26.71	23.3	1.92
23	1.42596	0.09118	26.66	23.3	1.92
24	1.42511	0.09116	26.61	23.3	1.92
25	1.42425	0.09114	26.56	23.3	1.92
26	1.42340	0.09112	26.50	23.3	1.92
27	1.42254	0.09111	26.45	23.3	1.92
28	1.42169	0.09109	26.40	23.3	1.92
29	1.42083	0.09107	26.35	23.3	1.92
30	1.41998	0.09106	26.30	23.3	1.92
31	1.41912	0.09104	26.24	23.3	1.92
32	1.41827	0.09103	26.19	23.3	1.92
33	1.41741	0.09102	26.14	23.3	1.92

Table 6-3. Expected TBR for normal fire missions with crew in BDU listed by round number. (Continued)

Round Number	*Log t*	*Std Dev Log t*	*t(sec)*	*Relative Error (%)*	*Standard Error of Mean (%)*
34	1.41656	0.09101	26.09	23.3	1.92
35	1.41570	0.09100	26.04	23.3	1.92
36	1.41485	0.09099	25.99	23.3	1.92
37	1.41399	0.09098	25.94	23.3	1.92
38	1.41314	0.09097	25.89	23.3	1.92
39	1.41229	0.09096	25.83	23.2	1.92
40	1.41143	0.09095	25.78	23.2	1.92
41	1.41058	0.09095	25.73	23.2	1.92
42	1.40972	0.09094	25.68	23.2	1.92
43	1.40887	0.09094	25.63	23.2	1.92
44	1.40801	0.09094	25.58	23.2	1.92
45	1.40716	0.09093	25.53	23.2	1.92
46	1.40630	0.09093	25.48	23.2	1.92
47	1.40545	0.09093	25.43	23.2	1.92
48	1.40459	0.09093	25.38	23.2	1.92
49	1.40374	0.09093	25.33	23.2	1.92
50	1.40288	0.09093	25.28	23.2	1.92
51	1.40203	0.09093	25.23	23.2	1.92
52	1.40117	0.09094	25.18	23.2	1.92
53	1.40032	0.09094	25.13	23.2	1.92
54	1.39946	0.09095	25.08	23.2	1.92
55	1.39861	0.09095	25.03	23.2	1.92
56	1.39775	0.09096	24.98	23.2	1.92
57	1.39690	0.09097	24.94	23.3	1.92
58	1.39604	0.09097	24.89	23.3	1.92
59	1.39519	0.09098	24.84	23.3	1.92
60	1.39434	0.09099	24.79	23.3	1.92
61	1.39348	0.09100	24.74	23.3	1.92
62	1.39263	0.09101	24.69	23.3	1.92
63	1.39177	0.09103	24.64	23.3	1.92
64	1.39092	0.09104	24.59	23.3	1.92
65	1.39006	0.09105	24.55	23.3	1.92
66	1.38921	0.09107	24.50	23.3	1.92
67	1.38835	0.09108	24.45	23.3	1.92

Table 6-3. Expected TBR for normal fire missions with crew in BDU listed by round number. (Continued)

Round Number	*Log t*	*Std Dev Log t*	*t(sec)*	*Relative Error (%)*	*Standard Error of Mean (%)*
68	1.38750	0.09110	24.40	23.3	1.92
69	1.38664	0.09112	24.35	23.3	1.92
70	1.38579	0.09114	24.31	23.3	1.92
71	1.38493	0.09116	24.26	23.3	1.92
72	1.38408	0.09118	24.21	23.3	1.92
73	1.38322	0.09120	24.16	23.3	1.92
74	1.38237	0.09122	24.11	23.3	1.92
75	1.38151	0.09124	24.07	23.3	1.92
76	1.38066	0.09126	24.02	23.3	1.92
77	1.37980	0.09129	23.97	23.3	1.92
78	1.37895	0.09131	23.93	23.3	1.92
79	1.37809	0.09134	23.88	23.4	1.93
80	1.37724	0.09136	23.83	23.4	1.93
81	1.37639	0.09139	23.78	23.4	1.93
82	1.37553	0.09142	23.74	23.4	1.93
83	1.37468	0.09145	23.69	23.4	1.93
84	1.37382	0.09148	23.64	23.4	1.93
85	1.37297	0.09151	23.60	23.4	1.93
86	1.37211	0.09154	23.55	23.4	1.93
87	1.37126	0.09157	23.51	23.4	1.93
88	1.37040	0.09160	23.46	23.4	1.93
89	1.36955	0.09164	23.41	23.4	1.93

$\log(t) = [1.446 - (8.55 \times 10^{-4})N\ ] \pm .09 \quad N \leq 100$

Expected mean log(TBR) and standard deviation for the N^{th} round fired; normal fire missions with crew in BDU.

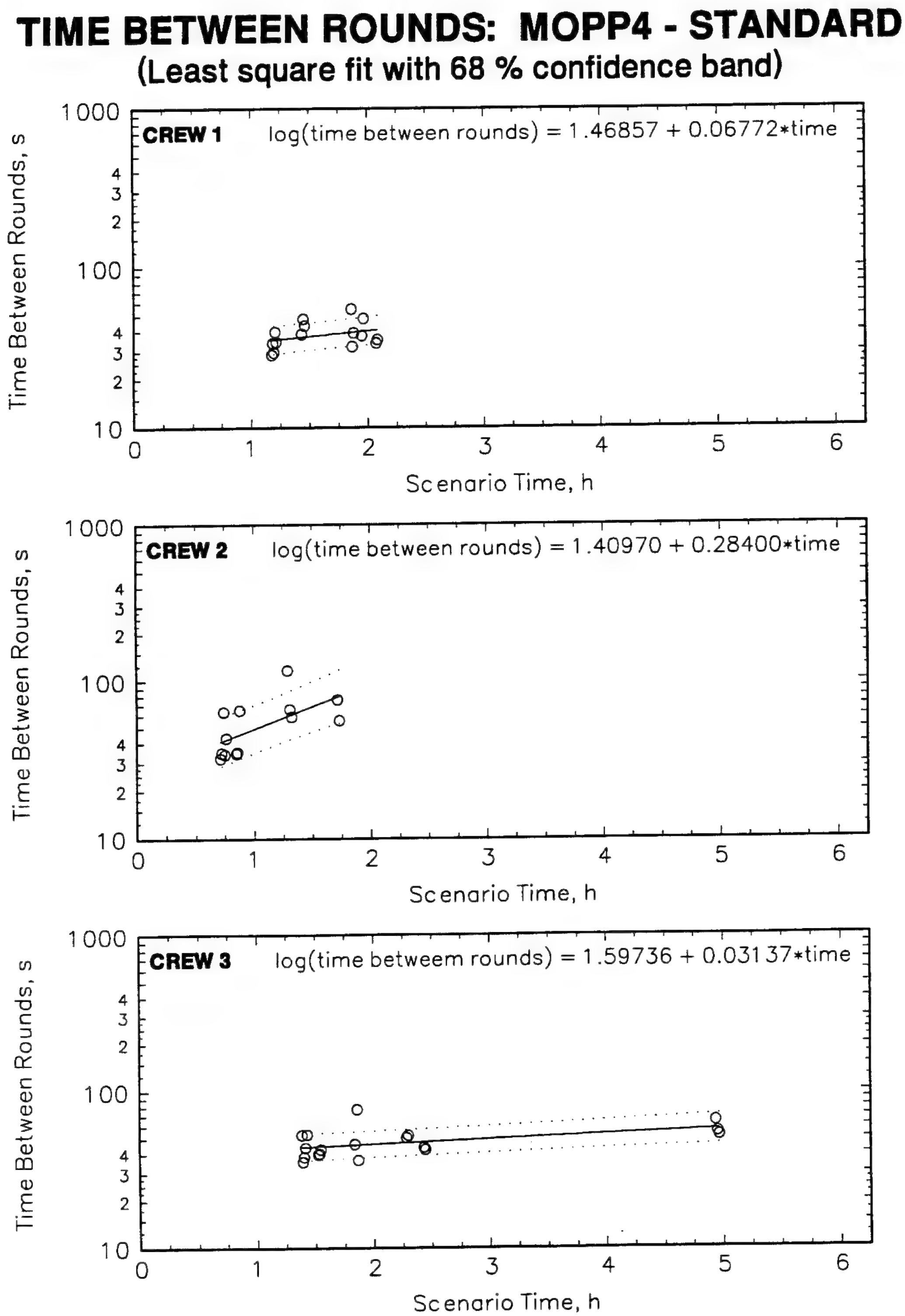

Figure 6-3. TBR for normal fire missions with crew in MOPP4 with standard crew positions (MOPP4-S)

Table 6-4. Statistical summary for TBR for normal fire missions in MOPP4 with standard crew positions (MOPP4-S).

log(time between rounds) = constant + slope*<mission time>

	Crew 1	*Crew 2*	*Crew 3*
Mean of Dependent Variable	1.57682	1.70706	1.66961
Number of Observations	15	13	18
Total Sum of Squares	0.08921	0.35547	0.12766
Residual Sum of Squares	0.08087	0.21756	0.10060
Std. Dev. of Estimate	0.07887	0.14064	0.07930
R-squared	0.09346	0.38795	0.21196
Adjusted R-squared	0.02372	0.33231	0.16271
Degrees of Freedom (df)	13	11	16
Number of Ind Vars (K)	2	2	2
F(K-1, df)	1.34021	6.97245	4.30349
Prob. Value of F	0.23723	0.02297	0.05453
Constant	1.46857	1.40970	1.59736
Standard error	0.09569	0.11918	0.03953
Slope	1.88e-5	7.89e-5	8.71e-6
Standard error	1.63e-5	2.99e-5	4.20e-6
t-ratio	1.15768	2.64054	2.07448
prob t	0.26782	0.02297	0.05453
Correlation Coefficient	0.30571	0.62286	0.46039

[1]Slope for each crew is measured in units of log(seconds) per second. Values quoted in Figures have been converted to log(seconds) per hour.

Table 6-5 summarizes the ANOVA test for the TBR data for the three crews in MOPP4-S and indicates statistically significant differences among them, probably due mainly to Crew 2. The overall mean value of log(TBR) is 1.650 with a standard deviation of 0.12. The corresponding TBR is 45 s for a time-averaged performance degradation of 42%.

Over time-in-MOPP4, the TBR data for MOPP4-S shows performance degradation increasing in the 30% to 50% range while the crews are still operating.

Table 6-5. ANOVA for TBR for normal fire missions with crews in MOPP4-S (Figure 6-3).

	Sum Sq	*DF*	*Mean Sq*
Crew	0.12959	2	0.06479
Error	0.57234	43	0.01331

Mean of Dep. Var.	1.64993
Number of Obs	46
Total Sum of Squares	0.70193
Residual Sum of Squares	0.57234
Std. Dev. of Estimate	0.11537
R-squared	0.18461
Adjusted R-squared	0.14669
Degrees of Freedom (df)	43
Number of Ind Vars (K)	3
F(K-1, df)	4.86785
Prob. Value of F	0.01243

6.1.3 MOPP4 With Rotating Crew Positions.

Because of technical difficulties on the first day of the exercise with Crew 1, only Crews 2 and 3 attempted a scenario in MOPP4 with rotating crew positions (MOPP4-R). Figure 6-4 presents the resulting TTFR's versus scenario time. Regression lines are plotted in Figure 6-4. Table 6-6 summarizes statistical information for the regression analyses. Once again, the more rapidly worsening performance for Crew 3 portends the earlier medical halt for this crew. They start fast and quickly deteriorate. Crew 2, on the other hand, maintains a moderate pace from the beginning and finishes the entire scenario. It will be interesting in further analysis try to determine the relative importance of pacing and environmental factors in allowing Crew 2 to complete its scenario. It's also interesting to note that both crews ended at roughly the same performance level. Is this TBR, around 45 s, mainly due to the slowing of heat stress or the loss of crew members?

The mean log(TBR) for Crews 2 and 3 are 1.618 and 1.548, respectively. The corresponding

TBR's are 41 s and 35 s compared to the central value of 26 s in BDU. Thus, the time averaged performance degradation is in the 25% to 35% range.

The ANOVA test for the normal fire missions of the two MOPP4-R scenarios is shown in Table 6-7. It shows a statistically significant difference between the two crews as noted in the preceding paragraph. It also provides an aggregated mean value for log(TBR) of 1.595 and a standard deviation of 0.09 corresponding to a TBR of 39 s. The aggregated time-averaged performance degradation is 33%.

6.1.4 Discussion of TBR Performance for Normal Fire Missions.

The baseline BDU data for time between round shows a significant practice or warm-up effect. On a daily basis after 17 fire missions with 89 rounds fired, the average TBR improves from 28 to 24 seconds. Table 6-3 includes a linear formula for the logarithm (to the base 10) of the mean TTFR versus round number and includes a standard deviation of .09 for the logarithm. For a Monte Carlo simulation in an engagement model, the logarithm of TBR for a given round number should be drawn at random from the appropriate normal distribution and then converted to a time in seconds. The formula should not be used for more than about 100 rounds since it is not known from this analysis after how many rounds performance in battle dress uniform levels out and then begins to deteriorate. The quoted standard deviation is from variation of crew performance during this exercise and has negligible contribution from measurement error.

The fire mission scenarios in MOPP4 indicate that rotating crew positions to distribute thermal-related work load among crew members increases the number of fire missions that can be accomplished with moderate heat stress. On the other hand, performance levels while still in action were not significantly different between rotating and standard crew positions for this exercise. Table 6-8 presents an analysis of variance for all five scenarios in which the crews operated in MOPP4. The test indicates significant differences among the five sets of normal mission TBR data in MOPP4. The logarithm of TBR for the five cases has a mean of 1.619 and a standard deviation of 0.11 corresponding to an average TBR of 42 s.

The performance degradation relative to BDU for time between rounds for normal fire missions with crews in MOPP4 averaged over all scenario times at which the crews are still operating is then 38%. Analysis accounting for the variation of mean TBR with time-in-MOPP4 will show a range of degradation.

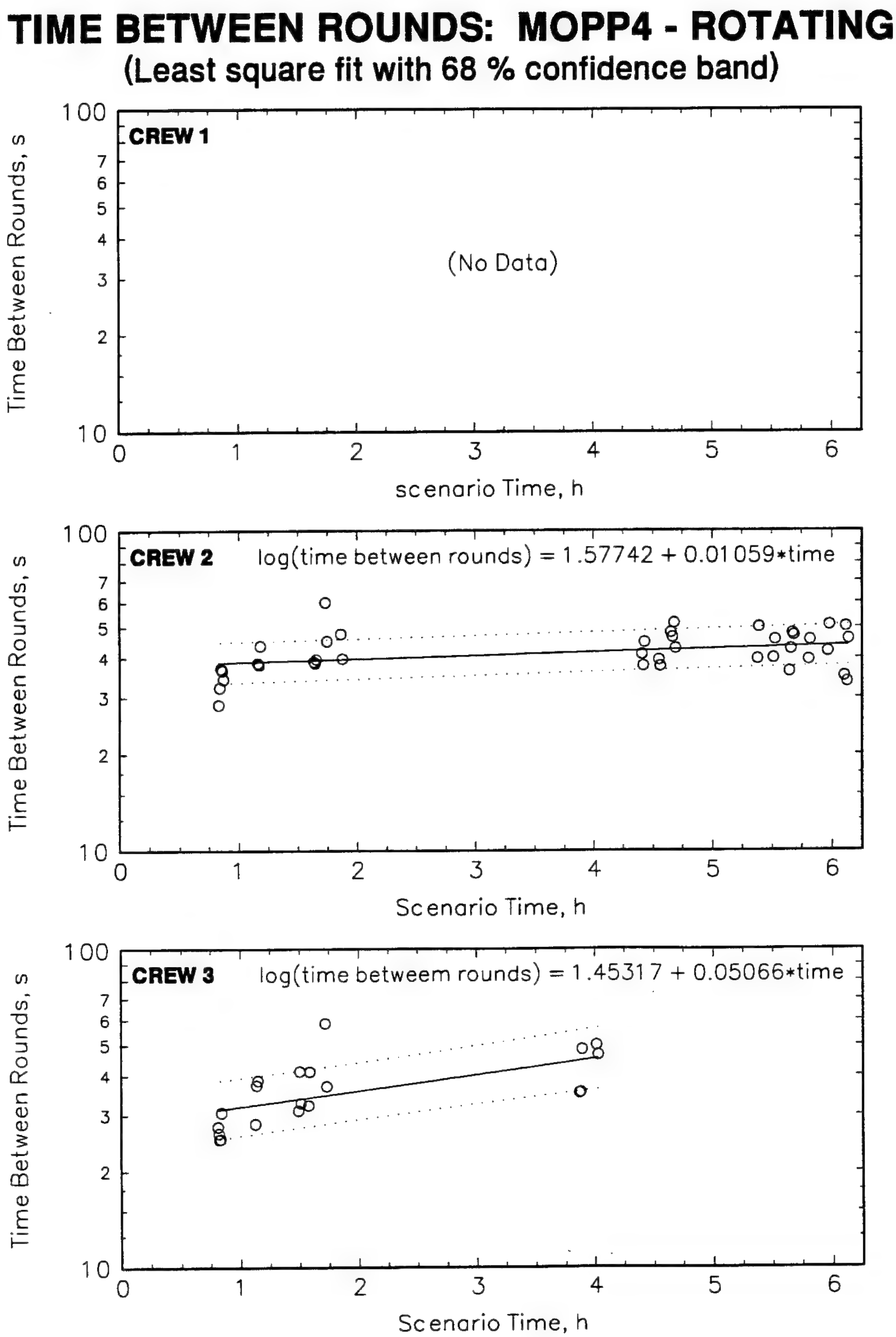

Figure 6-4. TBR for normal fire missions with crew in MOPP4 with rotating crew positions (MOPP4-R).

Table 6-6. Statistical summary for TBR for normal fire missions with crew in MOPP4 with rotating crew positions (MOPP4-R).

log(time between rounds) = constant + slope*<mission time>

	Crew 1	*Crew 2*	*Crew 3*
Mean of Dependent Variable		1.61805	1.54840
Number of Observations		40	20
Total Sum of Squares		0.15977	0.20641
Residual Sum of Squares		0.14143	0.13188
Std. Dev. of Estimate		0.06101	0.08560
R-squared		0.11475	0.36110
Adjusted R-squared		0.09146	0.32560
Degrees of Freedom (df)		38	18
Number of Ind Vars (K)		2	2
F(K-1, df)		4.92591	10.17337
Prob. Value of F		0.03250	0.00508
Constant		1.57442	1.45137
Standard error		0.02069	0.03594
Slope[1]		2.94e-6	1.41e-5
Standard error		1.33e-6	4.41e-6
t-ratio		2.21944	3.18957
prob t		0.03250	0.00508
Correlation Coefficient		0.33875	0.60092

[1]Slope for each crew is measured in units of log(seconds) per second. Values quoted in Figures have been converted to log(seconds) per hour.

Table 6-7. ANOVA for TBR for normal fire missions with crews in MOPP4-R (Figure 6-4).

	Sum Sq	*DF*	*Mean Sq*
Crew	0.06468	1	0.06468
Error	0.36618	58	0.00631

Mean of Dep. Var.	1.59483
Number of Obs.	60
Total Sum of Squares	0.43086
Residual Sum of Squares	0.36618
Std. Dev. of Estimate	0.07946
R-squared	0.15012
Adjusted R-squared	0.13547
Degrees of Freedom (df)	58
Number of Ind Vars (K)	2
F(K-1, df)	10.24492
Prob. Value of F	0.00222

Table 6-8. ANOVA for TBR for normal fire missions for all scenarios with crew in MOPP4 (MOPP4-S and MOPP4-R).

	Sum Sq	*DF*	*Mean Sq*
Crew	0.27333	4	0.06833
Error	0.93852	101	0.00929

Mean of Dep. Var.	1.61874
Number of Obs.	106
Total Sum of Squares	1.21185
Residual Sum of Squares	0.93852
Std. Dev. of Estimate	0.09640
R-squared	0.22555
Adjusted R-squared	0.19487
Degrees of Freedom (df)	101
Number of Ind Vars (K)	5
F(K-1, df)	7.35360
Prob. Value of F	0.00003

6.2 HIGH ANGLE FIRE MISSIONS.

This subsection presents time between rounds (TBR) data for high angle (HA) fire missions, that is, those with elevation angle more than 1000 milliradians. Each HA fire mission consists of 5 rounds delivered to a single aim point. For these missions, the barrel of the howitzer had to be depressed (elevation angle lowered) between rounds in order to load the powder and projectile for the next round. Each scenario had only two HA missions, both occurring before resupply. Because of the limited interval of scenario time covered by the high angle missions, TTFR is plotted only against round number.

Figure 6-5 presents TBR versus round number for the crews in battle dress uniform. Normal fire missions are counted in round number, so the two HA mission appear as separate clusters in the plots. Table 6-9 shows the statistical summary of the linear regressions included in Figure 6-5. The data for Crew 1 has no significant slope while that for Crew 3 has a definite negative slope. The data for Crew 2 has the same negative slope as Crew 3, but is statistically less significant. Table 6-10 presents an ANOVA test for the TBR data of Figure 6-5 showing that it is reasonable to aggregate the data from the three crews. The mean log(TBR) for these HA missions in BDU is 1.772 with a standard deviation of 0.043 corresponding to a TBR of 59 s.

Figure 6-6 presents the aggregated TBR data with crew in BDU plotted versus round number and includes the usual regression line whose statistical parameters are summarized in the All Crews column of Table 6-9. The regression shows a significant negative slope that has a chance of only 0.001 of being matched or exceeded at random. Thus, the BDU data for TBR at high angle shows a significant practice or warm-up effect, decreasing from about 63 to about 55 s over the measured interval with a time-averaged value of 59 s.

Figure 6-7 presents TBR versus round number for HA missions with crew in MOPP4-S. Each regression line in Figure 6-7 shows a positive slope indicative of performance degradation with time. Table 6-11 summarizes statistical data for each of the regression lines. The slope for Crew 1 is quite significant, that for Crew 3 less so, and that for Crew 2 not at all. The ANOVA presented in Table 6-12 indicates significant differences of data among the three crews. For example, Figure 6-7 shows that Crew 1 starts with a fast time but deteriorates rapidly to the same level as Crews 2 and 3. Crews 2 and 3 have similar regression lines but quite different standard deviations. The three crews have a mean log(TBR) of 1.909 corresponding to a TBR of 81 s. The corresponding performance degradation averaged over crew and rounds is 27%.

Figure 6-8 presents TBR versus round number for HA missions with crew in MOPP4-R. Table 6-13 summarizes statistical data for each of the regression lines plotted in Figure 6-8. Crew 2 shows a small negative slope and Crew 3 shows a small positive slope of its regression line, but neither is statistically significant. The negative slope for Crew 2 is dominated by the first two data points which seem to be outliers. Observer notes taken during the exercise indicate that there was trouble closing the breech on the first two rounds and that a second ram was required to properly seat the third projectile. These factors all contribute to the abnormally high

TIME BETWEEN ROUNDS (HIGH ANGLE): BDU

(Linear regression with 68 % confidence band)

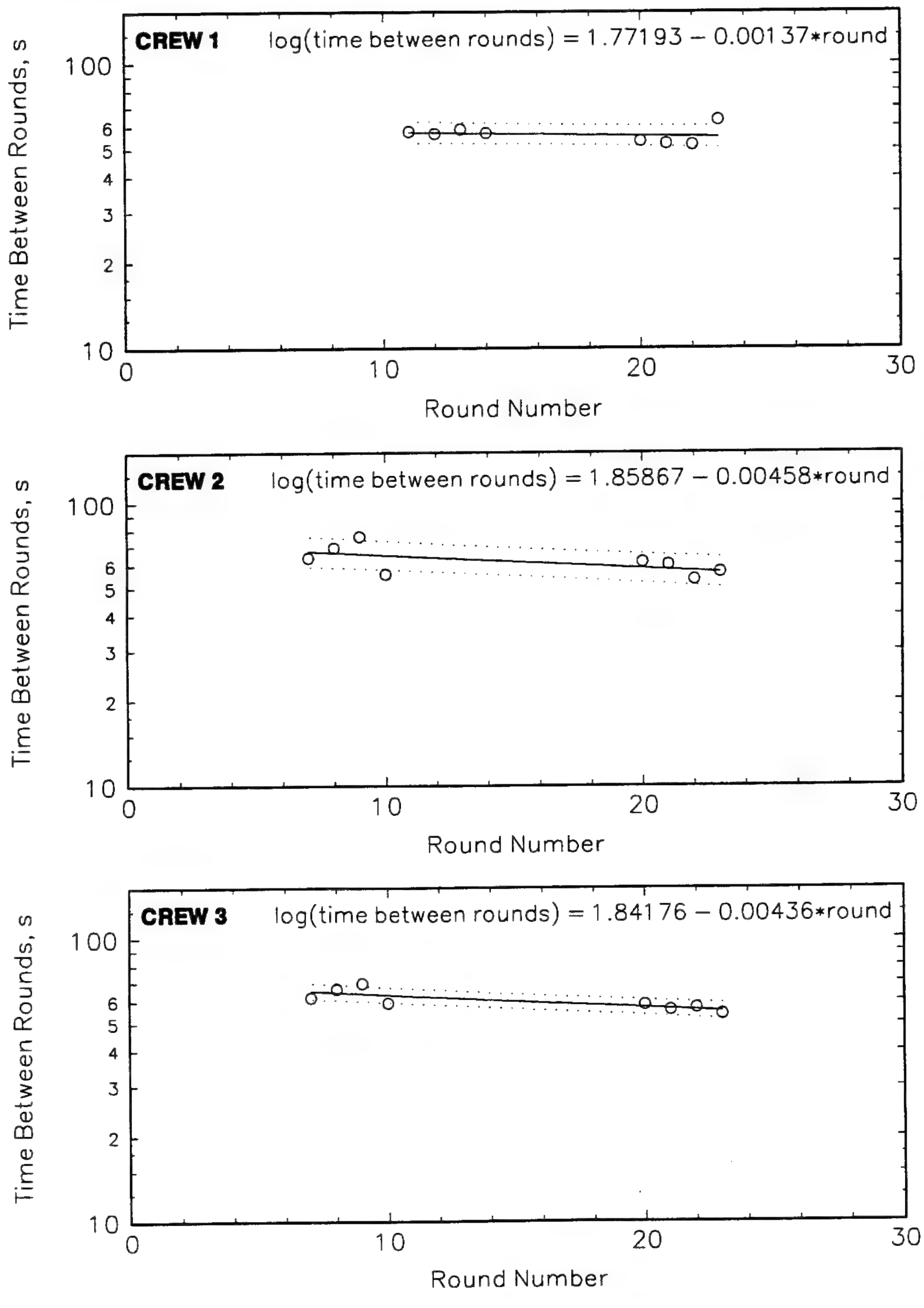

Figure 6-5. TBR for high angle (HA) missions with crew in BDU. Each scenario had only two 5-round HA fire missions.

Table 6-9. Statistical summary for TBR for high angle (HA) missions with crew in BDU.

log(time between rounds) = constant + slope*<round number>

	Crew 1	*Crew 2*	*Crew 3*	*All Crews*
Mean of Dependent Variable	1.74867	1.79000	1.77631	1.77166
Number of Observations	8	8	8	24
Total Sum of Squares	0.00577	0.01817	0.00967	0.04070
Residual Sum of Squares	0.00545	0.01087	0.00304	0.02519
Std. Dev. of Estimate	0.03015	0.04257	0.02252	0.03383
R-squared	0.05576	0.40150	0.68534	0.38126
Adjusted R-squared	-0.10161	0.30175	0.63290	0.35313
Degrees of Freedom (df)	6	6	6	22
Number of Ind Vars (K)	2	2	2	2
F(K-1, df)	0.35431	4.02500	13.06844	13.55590
Prob. Value of F	0.57343	0.09163	0.01116	0.00131
Constant	1.77193	1.85867	1.84176	1.83710
Standard error	0.04050	0.03739	0.01978	0.01907
Slope[1]	-0.00137	-0.00458	-0.00436	-0.00418
Standard error	0.00230	0.00228	0.00121	0.00113
t-ratio	-0.59524	-2.00624	-3.61503	-3.68183
prob t	0.57343	0.09163	0.01116	0.00131
Correlation Coefficient	-0.23613	-0.63364	-0.82785	-0.61746

[1]Slope is measured in units of log(seconds) per round number.

Table 6-10. ANOVA for TBR for HA missions with crews in BDU.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.00709	2	0.00355
Error	0.03361	21	0.00160

Mean of Dep. Var	1.77166
Number of Obs	24
Total Sum of Squares	0.04070
Residual Sum of Squares	0.03361
Std. Dev. of Estimate	0.04001
R-squared	0.17424
Adjusted R-squared	-0.09560
Degrees of Freedom (df)	21
Number of Ind Vars (K)	3
F(K-1, df)	22.21557
Prob. Value of F	0.13396

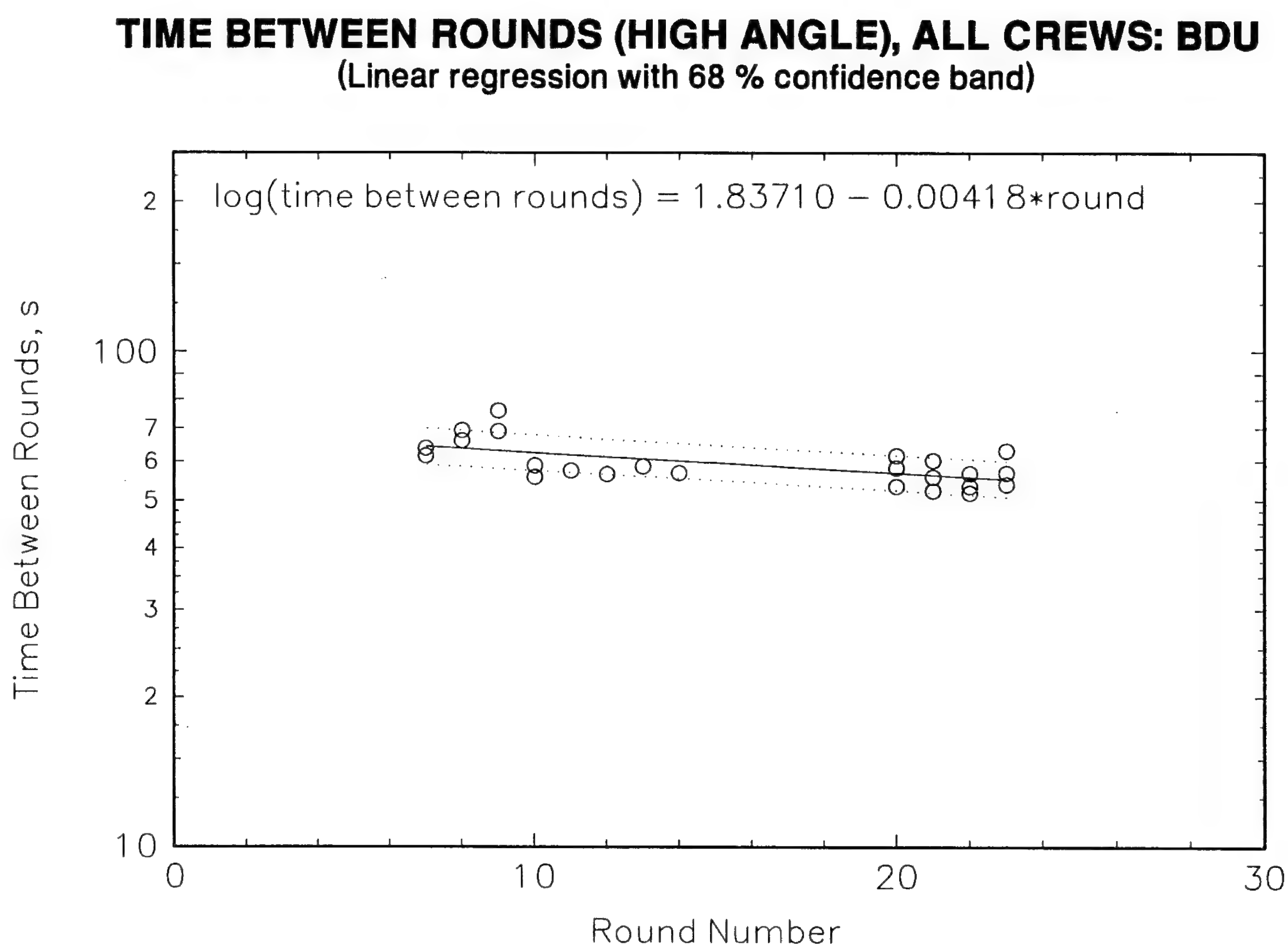

Figure 6-6. Aggregated data for TBR for HA fire missions with crews in BDU.

TIME BETWEEN ROUNDS (HIGH ANGLE): MOPP4 - S

(Linear regression with 68 % confidence band)

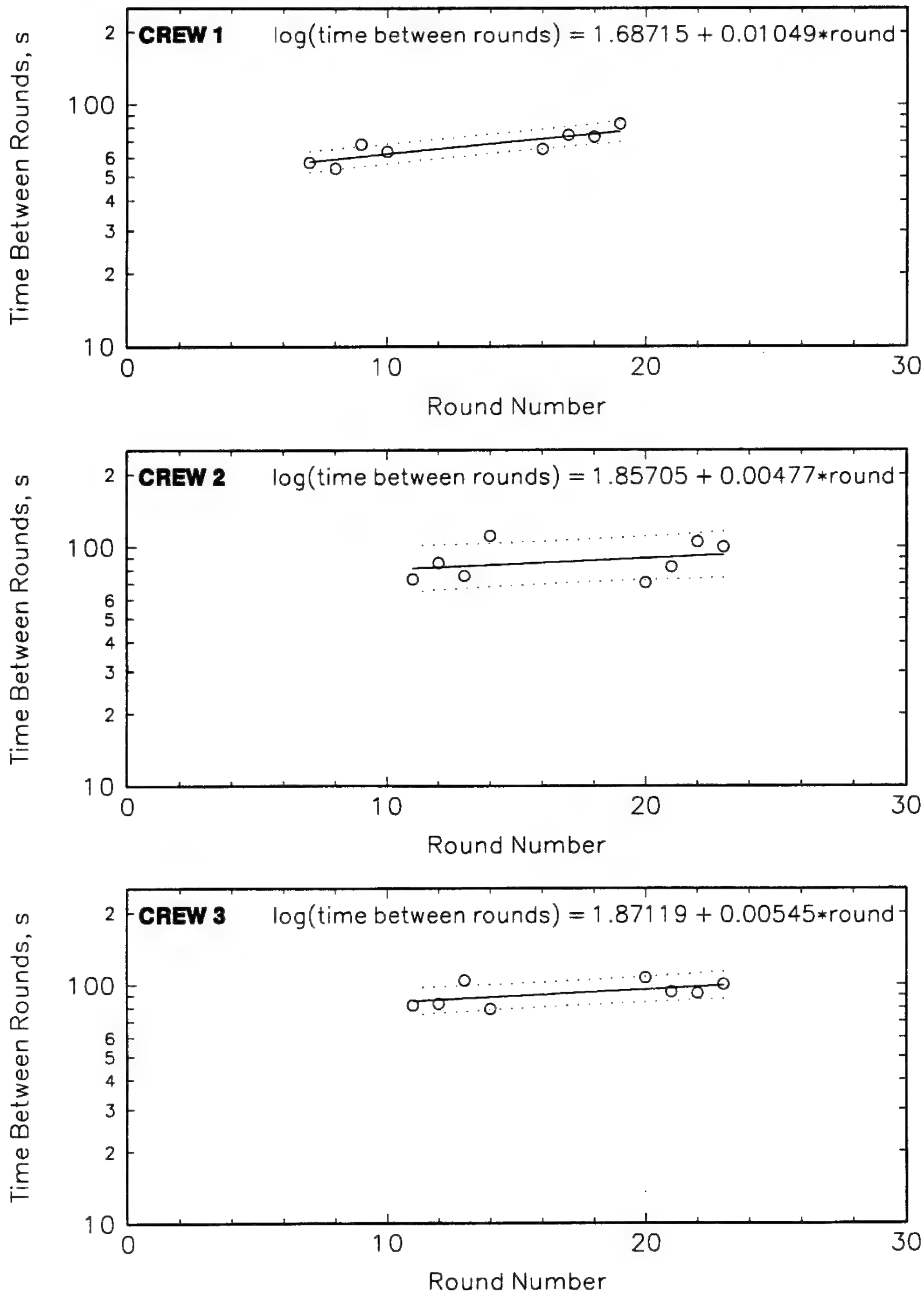

Figure 6-7. TBR for HA missions with the crews in MOPP4-S.

Table 6-11. Statistical summary for TBR for the HA missions with crews in MOPP4-S.

	Crew 1	*Crew 2*	*Crew3*
Mean of Dependent Variable	1.82357	1.93821	1.96387
Number of Observations	8	8	8
Total Sum of Squares	0.02601	0.03954	0.01731
Residual Sum of Squares	0.00707	0.03562	0.01220
Std. Dev. of Estimate	0.03433	0.07705	0.04509
R-squared	0.72816	0.09916	0.29533
Adjusted R-squared	0.68285	-0.05098	0.17789
Degrees of Freedom (df)	6	6	6
Number of Ind Vars (K)	2	2	2
F(K-1, df)	16.07183	0.66042	2.51465
Prob. Value of F	0.00705	0.44745	0.16389
Constant	1.68715	1.85705	1.87119
Standard error	0.03613	0.10352	0.06058
Slope[1]	0.01049	0.00477	0.00545
Standard error	0.00262	0.00587	0.00344
t-ratio	4.00897	0.81266	1.58577
prob t	0.00705	0.44745	0.16389
Correlation Coefficient	0.85332	0.31489	0.54344

[1]Slope is measured in units of log(seconds) per round number.

Table 6-12. ANOVA for TBR for HA missions with crews in MOPP4-S.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.08930	2	0.04465
Error	0.08286	21	0.00395

Mean of Dep. Var	1.90855
Number of Obs	24
Total Sum of Squares	0.17216
Residual Sum of Squares	0.08286
Std. Dev. of Estimate	0.06282
R-squared	0.51869
Adjusted R-squared	-0.47286
Degrees of Freedom (df)	21
Number of Ind Vars (K)	3
F(K-1, df)	211.31564
Prob. Value of F	0.00046

TIME BETWEEN ROUNDS (HIGH ANGLE): MOPP4 - R

(Linear regression with 68 % confidence band)

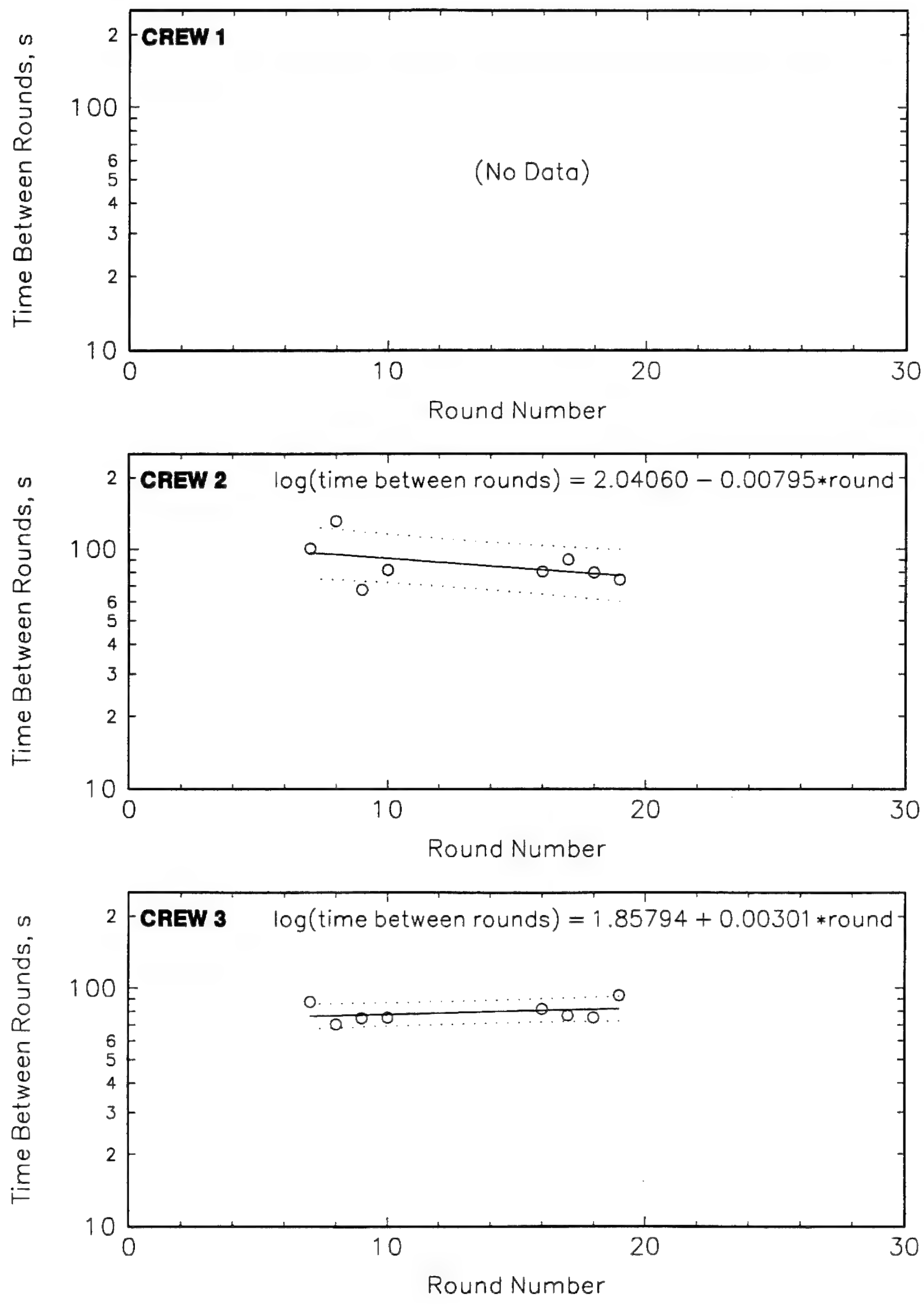

Figure 6-8. TBR for HA fire missions with the crews in MOPP4-R.

Table 6-13. Statistical summary for TBR for the HA fire missions with crews in MOPP4-R.

	Crew 1	*Crew 2*	*Crew 3*
Mean of Dependent Variable	No Data	1.93724	1.89713
Number of Observations		8	8
Total Sum of Squares		0.05564	0.01207
Residual Sum of Squares		0.04477	0.01050
Std. Dev. of Estimate		0.08638	0.04184
R-squared		0.19541	0.12953
Adjusted R-squared		0.06131	-0.01554
Degrees of Freedom (df)		6	6
Number of Ind Vars (K)		2	2
F(K-1, df)		1.45719	0.89287
Prob. Value of F		0.27280	0.38118
Constant		2.04060	1.85794
Standard error		0.09091	0.04403
Slope[1]		-0.00795	0.00301
Standard error		0.00659	0.00319
t-ratio		-1.20714	0.94492
prob t		0.27280	0.38118
Correlation Coefficient		-0.44205	0.35991

[1]Slope is measured in units of log(seconds) per round number.

first and second TBR intervals. The rest of the TBR intervals for Crew 2 fall in line with those of Crew 3. Table 6-14 presents an ANOVA test for the two groups of data showing that it is reasonable to aggregate the data. The mean log(TBR) for the high angle missions with crew in MOPP4-R is 1.917 with a standard deviation of 0.07 corresponding to a TBR of 83 s. The time-averaged performance degradation is then 29%.

Table 6-14. ANOVA for TBR for HA missions with crews in MOPP4-R.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.00644	1	0.00644
Error	0.06771	14	0.00484

Mean of Dep. Var.	1.91718
Number of Obs.	16
Total Sum of Squares	0.07415
Residual Sum of Squares	0.06771
Std. Dev. of Estimate	0.06954
R-squared	0.08680
Adjusted R-squared	0.02158
Degrees of Freedom (df)	14
Number of Ind Vars (K)	2
F(K-1, df)	1.33076
Prob. Value of F	0.26798

Generally, the MOPP4-R and MOPP4-S results for TBR are similar. Table 6-15 presents an ANOVA test for the aggregated data. It shows statistically significant differences among the crews in spite of their similarity. The mean log(TBR) averaged over all crews, times and MOPP scenarios is 1.912 with a standard deviation of 0.08 corresponding to a TBR of 82 s and a performance degradation of 28%. The fire missions contributing to this average occurred after time-in-MOPP4 of one to two hours.

6.3 ZONE AND SWEEP FIRE MISSIONS.

This subsection presents time between rounds (TBR) data for zone and sweep (ZS) fire missions. A ZS fire mission consists of 25 rounds with the aim point adjusted on each round to produce a 5 x 5 grid for the lay down pattern. Each scenario had only one ZS fire mission and it occurred after resupply.

Table 6-15. ANOVA for TBR for all HA missions with crews in MOPP4.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.09645	4	0.02411
Error	0.15057	35	0.00430

Mean of Dep. Var.	1.91200
Number of Obs.	40
Total Sum of Squares	0.24702
Residual Sum of Squares	0.15057
Std. Dev. of Estimate	0.06559
R-squared	0.39045
Adjusted R-squared	0.32079
Degrees of Freedom (df)	35
Number of Ind Vars (K)	5
F(K-1, df)	5.60489
Prob. Value of F	0.00135

Figure 6-9 presents time between rounds for the ZS fire missions of each crew plotted versus round number of the ZS mission. Table 6-16 provides a statistical summary for each of the regression lines plotted in Figure 6-9. Crew 1 shows the least variance and has no statistically significant slope to its regression line. Crew 3 has the largest variance and a significant negative slope indicating improving performance during the fire mission. The variance and negative slope, however, are influenced by apparent outliers for the TBR interval following rounds 5 and 9, and maybe 8. Regression in the absence of these three data points still gives a negative slope with a probability of F of 6.4%, at the edge of significance and a variance in line with Crew 1 (See Table 3-2). Crew 2 has the slowest average time, no significant slope, and a larger variance even after eliminating the potential outliers of rounds 4 and 5 (See Table 3-2).

Table 6-17 presents an ANOVA test for the three TBR groups in BDU. The large value of F indicates a probability of less than .00001 of obtaining variances from truly equivalent crews as large or larger than those observed. Thus, the three crews in this exercise show statistically significant differences in performance on time between rounds for the zone and sweep fire mission in BDU. Similar differences in TBR were apparent for normal fire missions.

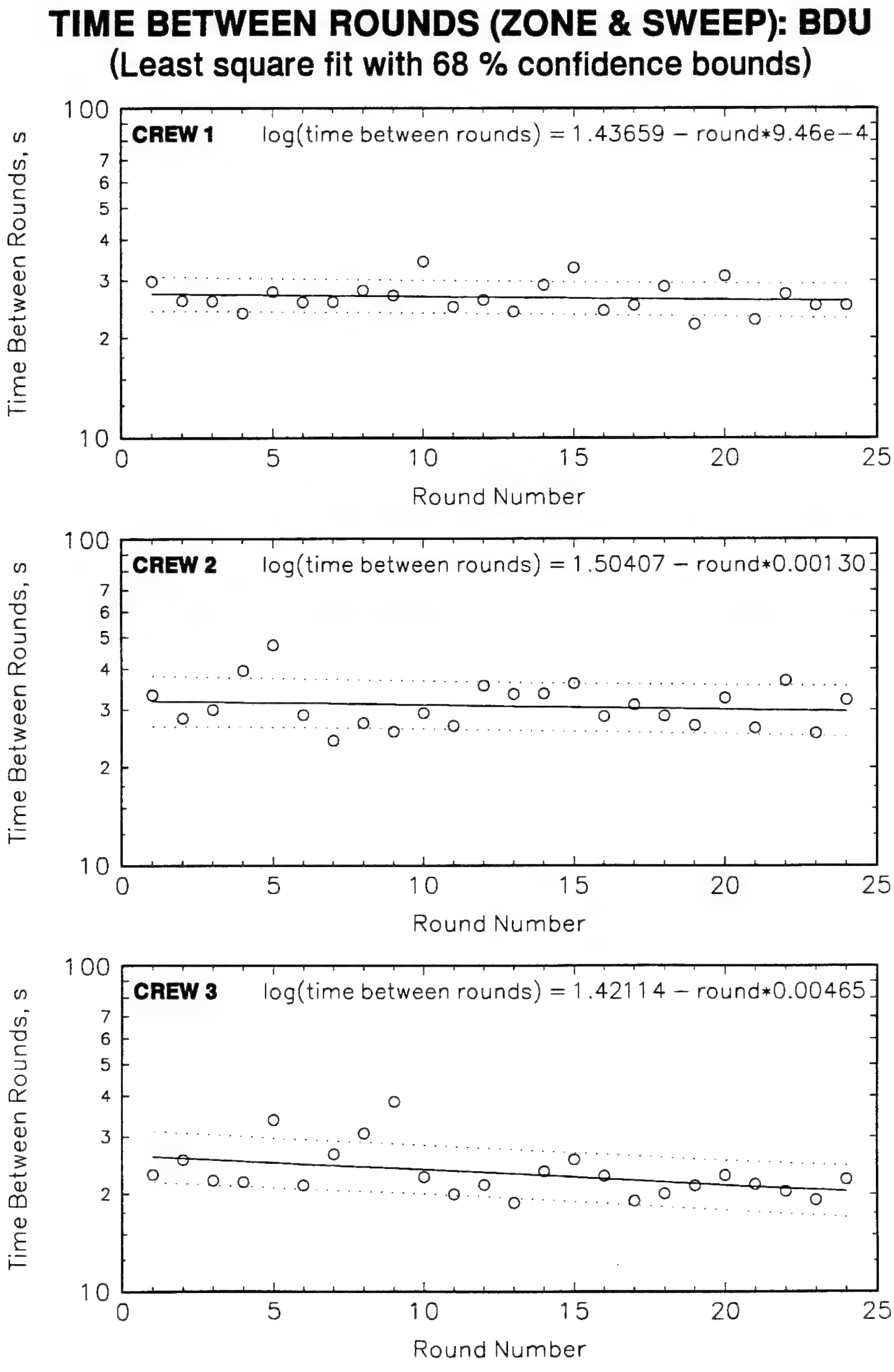

Figure 6-9. TBR for zone and sweep (ZS) fire missions with crew in BDU.

Table 6-16. Statistical summary for regression analyses of TBR for zone and sweep (ZS) fire missions with crews in BDU.

	Crew 1	*Crew 2*	*Crew 3*	*All Crews*
Mean of Dependent Variable	1.42476	1.48785	1.36297	1.42520
Number of Observations	24	24	24	72
Total Sum of Squares	0.05144	0.10938	0.13699	0.48498
Residual Sum of Squares	0.05041	0.10744	0.11209	0.46674
Std. Dev. of Estimate	0.04787	0.06988	0.07138	0.08166
R-squared	0.02000	0.01769	0.18179	0.03760
Adjusted R-squared	-0.02454	-0.02696	0.14460	0.02385
Degrees of Freedom (df)	22	22	22	70
Number of Ind Vars (K)	2	2	2	2
F(K-1, df)	0.44909	0.39628	4.88808	2.73464
Prob. Value of F	0.50974	0.53550	0.03774	0.10267
Constant	1.43659	1.50407	1.42114	1.45393
Standard error	0.02017	0.02945	0.03008	0.01986
Slope[1]	9.46E-4	-0.00130	-0.00465	-0.00230
Standard error	0.00141	0.00206	0.00210	0.00139
t-ratio	-0.67014	-0.62951	-2.21090	-1.65367
prob t	0.50974	0.53550	0.03774	0.10267
Correlation Coefficient	-0.14144	-0.13302	-0.42637	-0.19390

[1]Slope is measured in units of log(seconds) per round number.

Table 6-17. ANOVA for TBR for ZS fire missions with crews in BDU.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.18716	2	0.09358
Error	0.29781	69	0.00432

Mean of Dep. Var	1.42520
Number of Obs	72
Total Sum of Squares	0.48498
Residual Sum of Squares	0.29781
Std. Dev. of Estimate	0.06570
R-squared	0.38592
Adjusted R-squared	-0.36812
Degrees of Freedom (df)	69
Number of Ind Vars (K)	3
F(K-1, df)	221.68165
Prob. Value of F	0.00000

Even though the ANOVA test indicates significant differences among the crews, it is still useful to have an aggregate characterization of their performance. Figure 6-10 presents the aggregated TBR data plotted versus ZS round number. The solid dots indicate Crew 3 data which is significantly faster than average. The statistical summary for the regression line in Figure 6-10 is included in Table 6-14 under All Crews. Even though the aggregate regression has a negative slope, the prob t value of 10% indicates a low level of statistical significance even with inclusion of the early outliers discussed above. Ignoring dependence on round number, this aggregated data for ZS fire missions with crew in BDU has a mean log(TBR) of 1.425 with a standard deviation of 0.08. The corresponding TBR is 27 s.

Only two attempted scenarios in MOPP4 reached the zone and sweep mission, one for Crew 2 (MOPP4-R) and one for Crew 3 (MOPP4-S). Crew 3 managed to fire only 8 rounds before medical personnel halted their mission. Figure 6-11 presents TBR plotted versus ZS round number for these two scenarios. Table 6-16 provides a statistical summary for the regression analysis for Crew 2 and Table 6-17 for Crew 3.

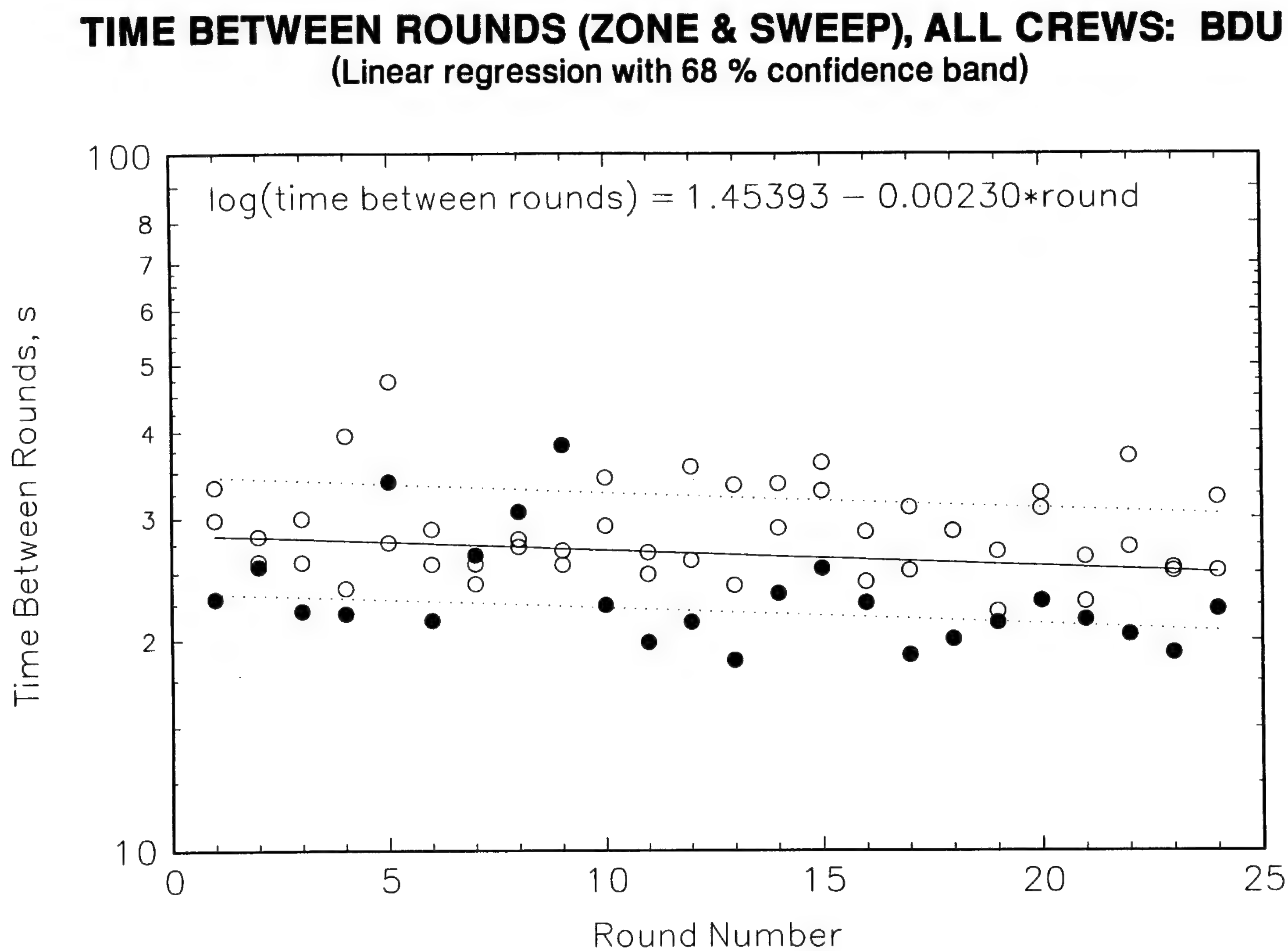

Figure 6-10. Aggregated data for TBR for HA fire missions with crews in BDU. Solid dots are Crew 3 data.

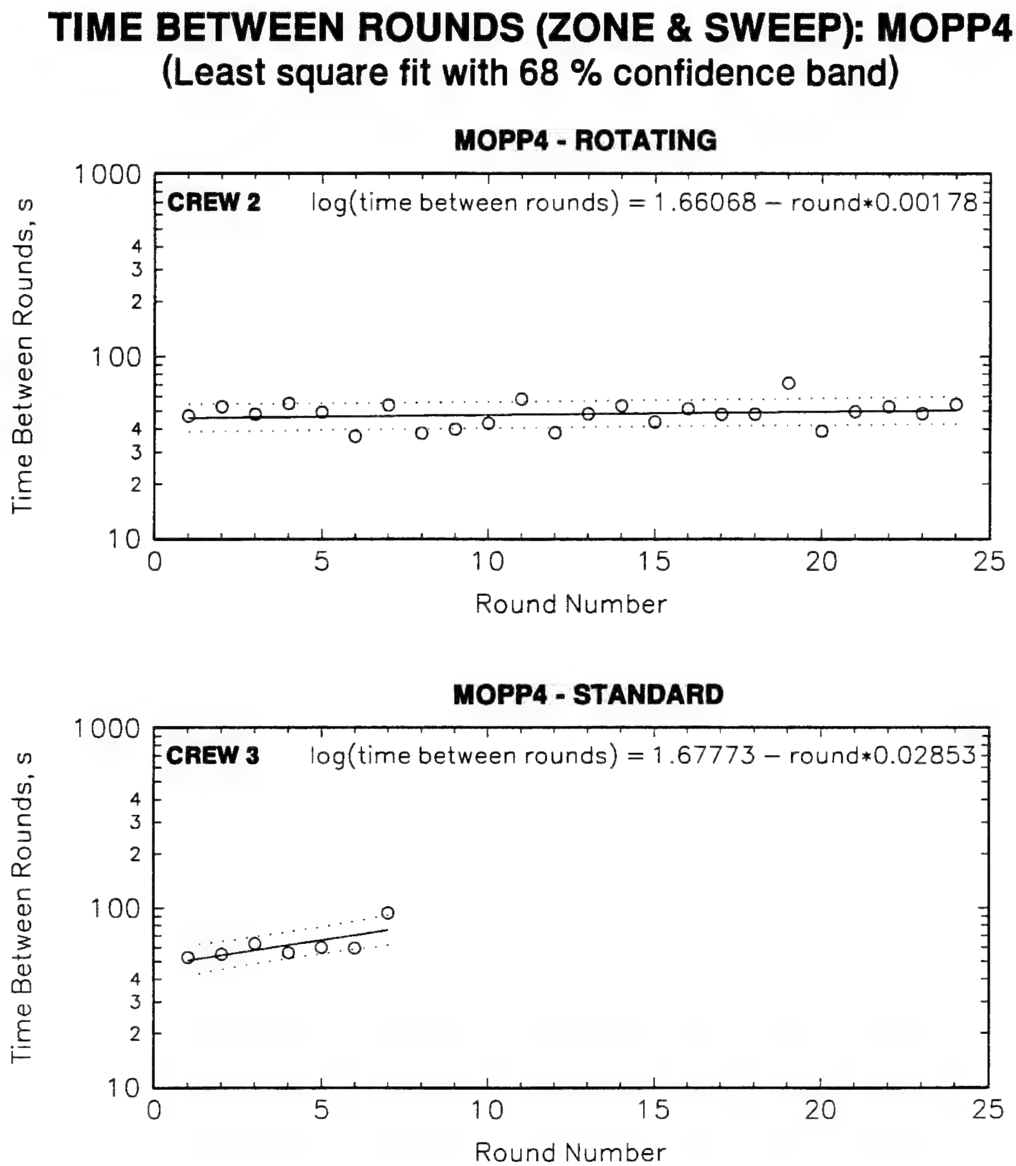

Figure 6-11. TBR for ZS fire missions with crews in MOPP4-R and MOPP4-S.

Table 6-18. Statistical summary for TBR for ZS fire mission for crew in MOPP4-R. Only crew 2 carried out this fire mission.

	Crew 1	*Crew 2*	*Crew 3*
Mean of Dependent Variable	No Data	1.68295	No Data
Number of Observations		24	
Total Sum of Squares		0.10675	
Residual Sum of Squares		0.10310	
Std. Dev. of Estimate		0.06846	
R-squared		0.03419	
Adjusted R-squared		-0.00971	
Degrees of Freedom (df)		22	
Number of Ind Vars (K)		2	
F(K-1, df)		0.77881	
Prob. Value of F		0.38705	
Constant		1.66068	
Standard error		0.02884	
Slope[1]		0.00178	
Standard error		0.00202	
t-ratio		0.88250	
prob t		0.38705	
Correlation Coefficient		0.18491	

[1]Slope is measured in units of log(seconds) per round number.

Table 6-19. Statistical summary for TBR for ZS fire mission for crew in MOPP4-S. Only Crew 3 reached this fire mission.

	Crew 1	*Crew 2*	*Crew 3*
Mean of Dependent Variable	No Data	No Data	1.79187
Number of Observations			7
Total Sum of Squares			0.04236
Residual Sum of Squares			0.01957
Std. Dev. of Estimate			0.06256
R-squared			0.53815
Adjusted R-squared			0.44578
Degrees of Freedom (df)			5
Number of Ind Vars (K)			2
F(K-1, df)			5.82600
Prob. Value of F			0.06059
Constant			1.67773
Standard error			0.05287
Slope[1]			0.02853
Standard error			0.01182
t-ratio			2.41371
prob t			0.06059
Correlation Coefficient			0.73359

[1]Slope is measured in units of log(seconds) per round number.

Crew 2 in MOPP4-R shows a good distribution of times with moderate variance and a small positive slope that is not statistically significant. The mean log(TBR) for Crew 2 is 1.683 with a standard deviation of 0.07. The corresponding TBR is 48 s for a performance degradation of 44% relative to BDU. This degradation is consistent with that observed for normal fire missions after resupply. Crew 2 was down one crew member for this fire mission.

Crew 3 in MOPP4-S was operating with seven crew members for its ZS fire mission. The fire mission was halted after 8 rounds when another ammo man was pulled by medical personnel. Figure 6-11 shows that the performance at the beginning of the ZS fire mission was on par with that of Crew 2 but was deteriorating. The mean log(TBR) for the seven TBR intervals was 1.792 with a standard deviation of 0.08. The corresponding TBR is 62 s for an average performance degradation of 56% relative to BDU.

Table 6-20 presents the results of an ANOVA test for consistency of the two sets of ZS data in MOPP4. It shows a low value of the probability of F indicating significant difference between the two data sets as noted in the preceding paragraph. As a typical value for the degradation of performance on time between rounds for zone and sweep missions, it is probably best to use the value of 44% from Crew 2 which was able to complete its fire mission. This mission occurred after about 5 hours in MOPP4.

Table 6-20. ANOVA for TBR for all ZS fire missions with crews in MOPP4.

	Sum Sq	*DF*	*Mean Sq*
Crew	0.06430	1	0.06430
Error	0.14911	29	0.00514

Mean of Dep. Var.	1.70754
Number of Obs.	31
Total Sum of Squares	0.21341
Residual Sum of Squares	0.14911
Std. Dev. of Estimate	0.07171
R-squared	0.30128
Adjusted R-squared	0.27719
Degrees of Freedom (df)	29
Number of Ind Vars (K)	2
F(K-1, df)	12.50452
Prob. Value of F	0.00139

SECTION 7
CONCLUSION

This report presents a good statistical characterization of the time to first round and the time between rounds for fire missions in battle dress uniform. These results are the baseline against which performance in MOPP4 is measured. The baseline results show a small, statistically significant improvement of performance with repetition, indicating a measurable practice or warm-up effect. The same firing time intervals are presented on a crew-by-crew basis versus time-in-MOPP4. These results show a clear trend of degrading performance with increasing time-in-MOPP4 attributable to both accumulating heat stress and diminishing crew size as individual crew members exceed the physiological limits of the test.

Table 7-1 presents a summary of TTFR and TBR data and the resulting MOPP4 performance ratios averaged over all times in MOPP4 for the aggregated MOPP4-S and MOPP4-R results. The measurements of performance degradation for TTFR are statistically equivalent for the three fire mission types, since the 1 standard error (s.e.) ranges overlap. On the other hand, the performance degradation of TBR is significantly different for each fire mission type. The higher statistical precision of TBR due to the larger number of measurements contributes to these differences. In addition, differences in tasks between rounds for the three types of fire missions may also contribute, especially for the zone and sweep missions for which the degradation is most severe. Comparison within the same fire mission type shows statistically equivalent performance degradation of TTFR and TBR for normal and high angle fire missions but more degradation of TBR than TTFR for zone and sweep missions.

This report also presents measured emplacement and displacement times for crews in battle dress uniform and MOPP4 as summarized in Table 4-5. There is minimal performance degradation within the first half hour of donning MOPP4 for laying the howitzer and setting up the ammo stacks. On the other hand, after 2 to 4 hours in MOPP4, there are significant degradations of 30% to 40% for laying the howitzer, ammo set up, and howitzer displacement.

The goal of this effort is to provide performance degradation as a function of time for operations in MOPP4. Certain issues require further analysis before such degradation functions can be confidently provided. The central issue involves the choice of independent variable for interpolation and extrapolation of performance. Time-in-MOPP4 is an obvious candidate. However, the associated heat stress depends on ambient conditions and activity level while in MOPP4. A second candidate is some physiological measure of heat strain such as core body temperature or heart rate.

Choice of independent variable will directly affect the separation of performance degradation into components due to the encumbrance of MOPP4 and the heat stress associated with MOPP4. One technique of separation is to extrapolate a series of performance measurements for a task back to zero time-in-MOPP4. The residual degradation may be attributed to encumbrance under

the assumption that heat stress takes some time to accumulate. The outcome of extrapolation depends on the choice of independent variable.

A second issue involves variation of the number of crew members performing as a function of time. The number was always 10 for the baseline data. However, it varied between 10 and 7 for MOPP4-S and 9 and 7 for MOPP4-R. One approach is to ignore the variation and consider it as an implicit effect of the heat stress of MOPP4. Another is to use conditional probabilities to account separately for the likely number of crew members present and the likely performance of these remaining crew members.

The generation of performance degradation functions for the M198 howitzer with crew in MOPP4 awaits analysis of these issues. Volume II of this report addresses these issues and presents analysis of individual tasks during fire missions.

Table 7-1. Summary of rates of fire and MOPP4 performance ratio (P) for each type of fire mission averaged over all times in MOPP4; includes both MOPP4-S and MOPP4-R data.

	Time to first round			*Time between rounds*		
	Normal	HA	ZS	Normal	HA	ZS
log(time,s) ± s.e. BDU	1.6686 ±.0088	1.9440 ±.0260	1.754 ±.014	1.4049 ±.0085	1.7717 ±.0086	1.4252 ±.0097
log(time,s) ± s.e. MOPP4	1.8726 ±.0168	2.092 ±.035	1.914 ±.034	1.6187 ±.0104	1.9120 ±.0126	1.7075 ±.0151
log(P) ± s.e.	-0.2040 ±.0190	-0.148 ±.044	-0.160 ±.037	-0.2138 ±.0134	-0.1403 ±.0153	-0.2823 ±.0179
P + 1 s.e.	0.653	0.787	0.753	0.630	0.750	0.544
Performance P	0.625	0.711	0.692	0.611	0.724	0.522
P - 1 s.e.	0.598	0.643	0.635	0.593	0.699	0.501

SECTION 8
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APPENDIX
SOLAR INSOLATION DATA

This Appendix presents analysis of the hourly average solar insolation values for each day of the exercise. Hourly average values are connected with a cubic spline interpolation curve and then integrated over the period of the day's exercise to provide an average solar insolation in watts per square meter during the exercise.

Each page of this Appendix presents calculations for one exercise day. The calculations and printouts were done with the MathCAD software program from MathSoft, Inc., Cambridge, Massachusetts. The argument of the READPRN function at the upper left of each page indicates the date of the exercise day. The solar insolation data is plotted for each day with both linear and cubic spline interpolation curves. The exercise interval is indicated by a bracket on the graph. The exercise start and stop times, the integrated solar heating (heat) and the average solar insolation (aveheat) are summarized in the lower right hand corner of each page.

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

$a := \mathrm{READPRN}(aug10)$

Start $\quad t1 := 9.63 \quad$ Decimal time, EST

Stop $\quad t2 := 14.91 \quad$ " $\quad$ "

$Na := \mathrm{length}\left[a^{\langle 0\rangle}\right]$

$j := 0 \,..\, Na - 1$

$Na = 12$

$s := a^{\langle 1\rangle}$ $\quad$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0\rangle} - .5$ $\quad$ t is vector of time points

Time EST / Ave. W/m2 previous hour

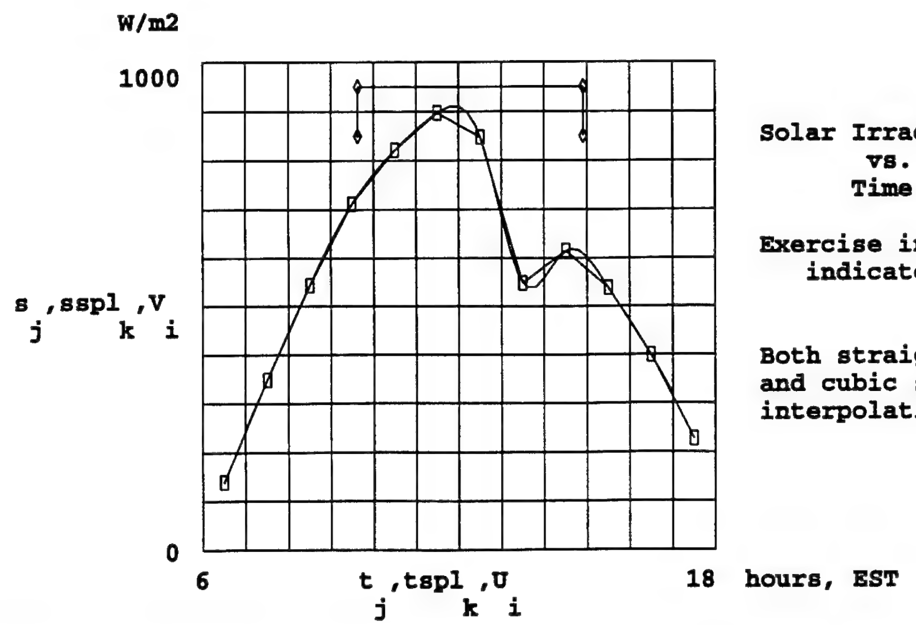
$$a = \begin{bmatrix} 7 & 139.8 \\ 8 & 349.2 \\ 9 & 544.1 \\ 10 & 711.6 \\ 11 & 820.8 \\ 12 & 897.1 \\ 13 & 847.9 \\ 14 & 548.5 \\ 15 & 614.9 \\ 16 & 538.3 \\ 17 & 399.4 \\ 18 & 227.4 \end{bmatrix}$$

$i := 0 \,..\, 3$

$$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix} \qquad U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$$

$cs := \mathrm{pspline}(t,s) \qquad k := 0 \,..\, 50 \qquad tspl_k := 7 + .2 \cdot k$

$sspl := \mathrm{interp}(cs,t,s,tspl)$ $\quad$ Cubic spline through solar irrad.



Solar Irradiance vs. Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

$S(arg) := \mathrm{interp}(cs,t,s,arg)$

$t1 = 9.63$ $\quad$ Start scenario

$t2 = 14.91$ $\quad$ Stop time

$$heat := \int_{t1}^{t2} S(T)\, dT$$

$heat = 3.943 \cdot 10^{3}$ $\quad$ W/m2 * hours

$$aveheat := \frac{heat}{t2 - t1}$$

$aveheat = 746.837$ $\quad$ W/m2

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

$a := \mathrm{READPRN}(aug12)$

Start $t1 := 9.29$ Decimal time, EST

Stop $t2 := 11.38$ " "

$Na := \mathrm{length}\left[a^{\langle 0\rangle}\right]$

$j := 0 \,..\, Na - 1$

$Na = 12$

$s := a^{\langle 1\rangle}$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0\rangle} - .5$ t is vector of time points

Time EST	Ave. W/m2 previous hour
7	117.4
8	261.7
9	498.7
10	664.5
11	701.7
12	723.1
13	853.5
14	681.4
15	673.6
16	390.5
17	352.3
18	226.5

(a = the matrix above)

$i := 0 \,..3$

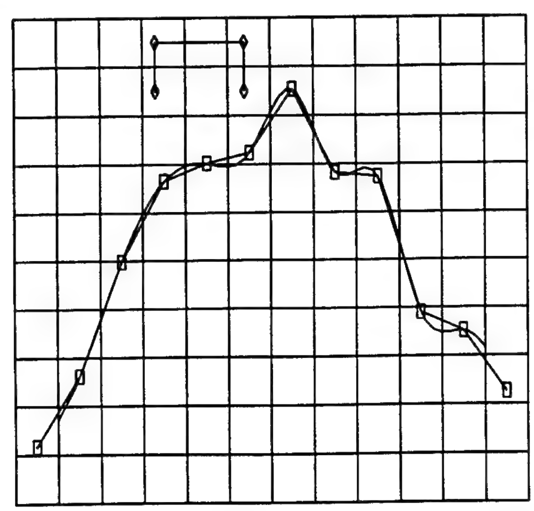
$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix}$

$U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$

$cs := \mathrm{pspline}(t,s)$ $k := 0 \,..50$ $tspl_k := 7 + .2 \cdot k$

$sspl := \mathrm{interp}(cs,t,s,tspl)$ Cubic spline through solar irrad.

W/m2



$s_j, sspl_k, V_i$

$t_j, tspl_k, U_i$ hours, EST

Solar Irradiance vs. Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

$S(arg) := \mathrm{interp}(cs,t,s,arg)$

$$heat := \int_{t1}^{t2} S(T)\, dT$$

$$aveheat := \frac{heat}{t2 - t1}$$

$t1 = 9.29$ Start scenario

$t2 = 11.38$ Stop time

$heat = 1.444 \cdot 10^{3}$ W/m2 * hours

$aveheat = 691.072$ W/m2

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

a := READPRN(aug14)

Start $t1 := 8.67$ Decimal time, EST

Stop $t2 := 12.59$ " "

$Na := \mathrm{length}\left[a^{<0>}\right]$

$j := 0 \,..\, Na - 1$

$Na = 12$

$s := a^{<1>}$ s is vector of ave. solar irrad. for previous hour

$t := a^{<0>} - .5$ t is vector of time points

Time EST	Ave. W/m2 previous hour
7	34.6
8	96.8
9	313.1
10	422.5
11	514.3
12	454.7
13	355.6
14	272.2
15	227.4
16	180.6
17	93.5
18	38.2

(a = the matrix above)

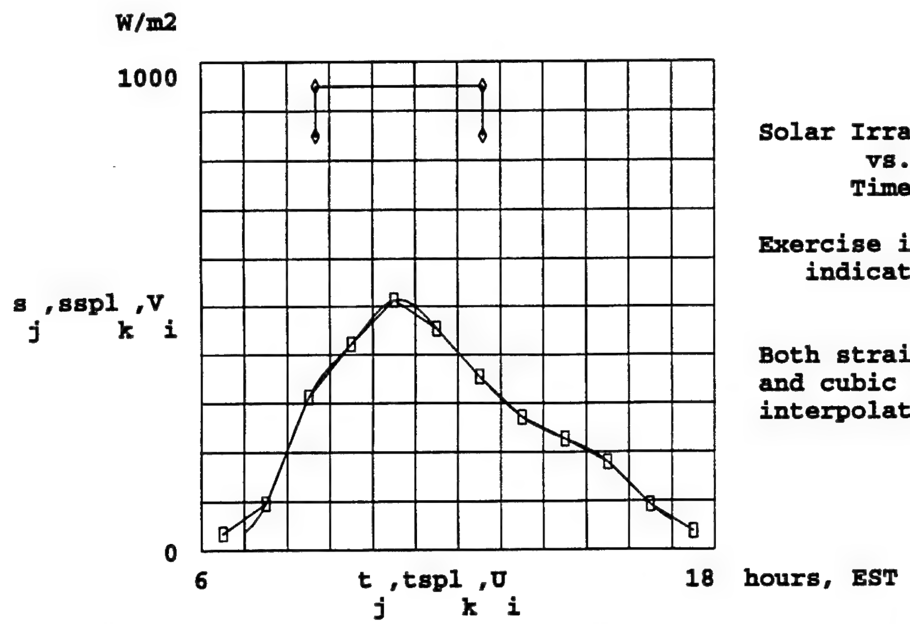
$i := 0 \,..\, 3$

$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix}$

$U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$

cs := pspline(t,s) $k := 0 \,..\, 50$ $tspl_k := 7 + .2 \cdot k$

$sspl := \mathrm{interp}(cs,t,s,tspl)$ Cubic spline through solar irrad.



Solar Irradiance vs. Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

$S(arg) := \mathrm{interp}(cs,t,s,arg)$

$t1 = 8.67$ Start scenario

$t2 = 12.59$ Stop time

$$heat := \int_{t1}^{t2} S(T)\, dT$$

$heat = 1.724 \cdot 10^{3}$ W/m2 * hours

$$aveheat := \frac{heat}{t2 - t1}$$

$aveheat = 439.899$ W/m2

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

$a := \mathrm{READPRN}(aug17)$

Start $\quad t1 := 9.15 \quad$ Decimal time, EST

Stop $\quad t2 := 13.01 \quad$ " $\quad$ "

$Na := \mathrm{length}\left[a^{\langle 0 \rangle}\right]$

$j := 0 \,..Na - 1$

$Na = 12$

$s := a^{\langle 1 \rangle}$ $\quad$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0 \rangle} - .5$ $\quad$ t is vector of time points

$a =$

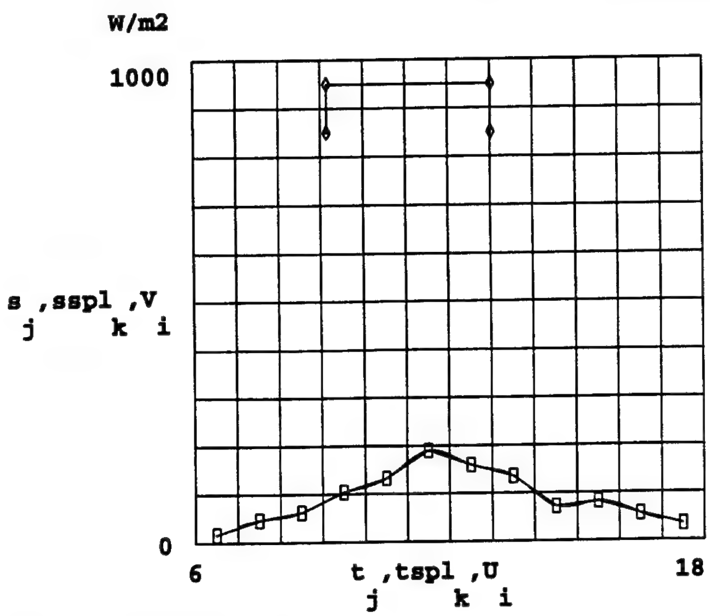
Time EST	Ave. W/m2 previous hour
7	17.3
8	46.2
9	62.6
10	103.5
11	132.1
12	190.9
13	159.7
14	135.8
15	72.1
16	82.2
17	55.5
18	34.2

$i := 0 \,..3$

$$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix} \qquad U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$$

$cs := \mathrm{pspline}(t,s) \qquad k := 0 \,..50 \qquad tspl_k := 7 + .2 \cdot k$

$sspl := \mathrm{interp}(cs,t,s,tspl)$ $\quad$ Cubic spline through solar irrad.



Solar Irradiance vs. Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

$S(arg) := \mathrm{interp}(cs,t,s,arg)$

$$heat := \int_{t1}^{t2} S(T)\, dT$$

$$aveheat := \frac{heat}{t2 - t1}$$

$t1 = 9.15$ $\quad$ Start scenario

$t2 = 13.01$ $\quad$ Stop time

$heat = 572.423$ $\quad$ W/m2 * hours

$aveheat = 148.296$ $\quad$ W/m2

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

$a := \mathrm{READPRN}(aug19)$

Start $t1 := 8.67$ Decimal time, EST

Stop $t2 := 10.40$ " "

$Na := \mathrm{length}\left[a^{\langle 0\rangle}\right]$

$j := 0 ..Na - 1$

$Na = 12$

$s := a^{\langle 1\rangle}$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0\rangle} - .5$ t is vector of time points

Time EST	Ave. W/m2 previous hour
7	106.8
8	272.2
9	483.2
10	651.9
11	766.2
12	736.2
13	733.4
14	640.8
15	446.2
16	290
17	52.5
18	52.3

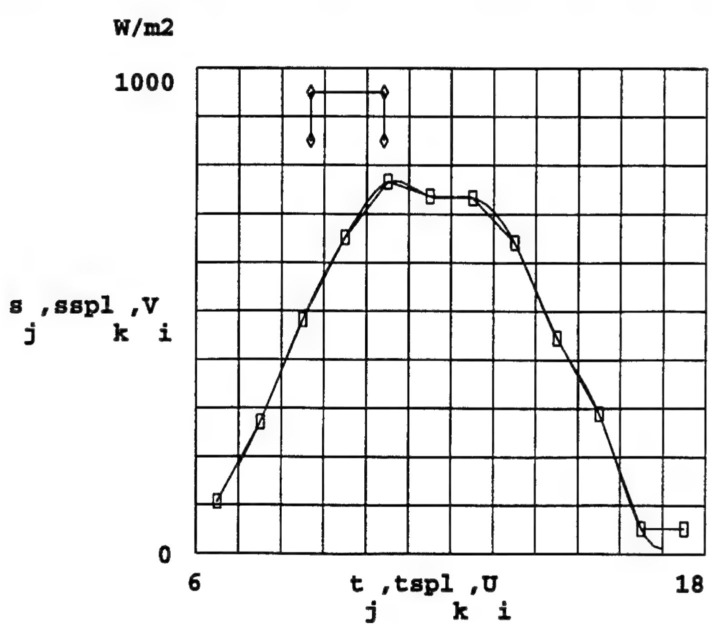
$a =$ (the matrix above)

$i := 0 ..3$

$$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix} \qquad U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$$

$cs := \mathrm{pspline}(t,s)$ $k := 0 ..50$ $tspl_k := 7 + .2 \cdot k$

$sspl := \mathrm{interp}(cs,t,s,tspl)$ Cubic spline through solar irrad.



hours, EST

Solar Irradiance vs. Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

$S(arg) := \mathrm{interp}(cs,t,s,arg)$

$t1 = 8.67$ Start scenario

$t2 = 10.4$ Stop time

$$heat := \int_{t1}^{t2} S(T)\, dT$$

$heat = 1.129 \cdot 10^{3}$ W/m2 * hours

$$aveheat := \frac{heat}{t2 - t1}$$

$aveheat = 652.596$ W/m2

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

a := READPRN(aug21)

Start $t1 := 8.59$ Decimal time, EST

Stop $t2 := 14.73$ " "

$Na := \mathrm{length}\left(a^{\langle 0 \rangle}\right)$

$j := 0 \,..\, Na - 1$

$Na = 12$

$s := a^{\langle 1 \rangle}$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0 \rangle} - .5$ t is vector of time points

a =

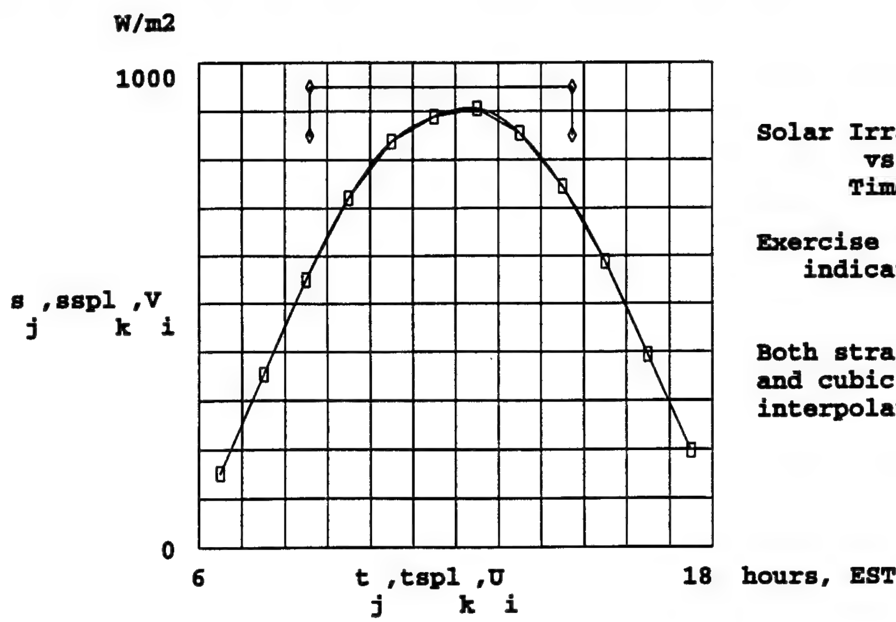
Time EST	Ave. W/m2 previous hour
7	152.2
8	354.4
9	550.5
10	721.4
11	837.8
12	888.9
13	906.2
14	854.9
15	744.9
16	587.4
17	394.2
18	198.4

$i := 0 \,..\, 3$

$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix}$ $U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$

cs := pspline(t,s) $k := 0 \,..\, 50$ $tspl_k := 7 + .2 \cdot k$

sspl := interp(cs,t,s,tspl) Cubic spline through solar irrad.



Solar Irradiance
vs.
Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

S(arg) := interp(cs,t,s,arg) $t1 = 8.59$ Start scenario

$t2 = 14.73$ Stop time

$$heat := \int_{t1}^{t2} S(T)\, dT$$

$heat = 5.001 \cdot 10^{3}$ W/m2 * hours

$$aveheat := \frac{heat}{t2 - t1}$$

$aveheat = 814.519$ W/m2

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

a := READPRN(aug24)

Start t1 := 8.72   Decimal time, EST

Stop t2 := 13.92 " "

Na := length$\left(a^{\langle 0 \rangle}\right)$

j := 0 ..Na - 1

Na = 12

$s := a^{\langle 1 \rangle}$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0 \rangle} - .5$ t is vector of time points

Time EST	Ave. W/m2 previous hour
7	107.3
8	215.3
9	524.9
10	667.8
11	796.9
12	865.5
13	851.4
14	795.9
15	712
16	533.6
17	361.4
18	170

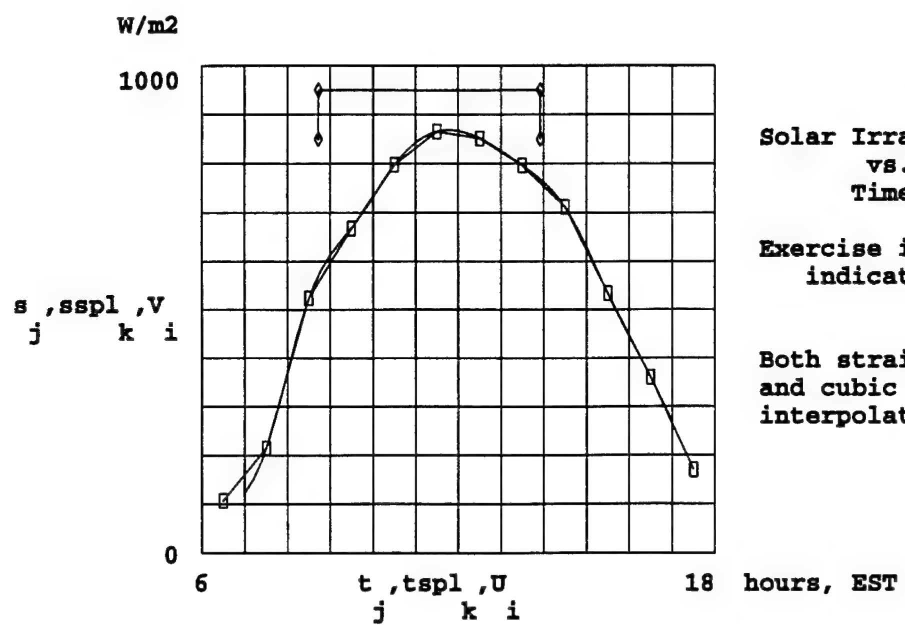
(a = the matrix above)

i := 0 ..3

$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix}$ $U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$

cs := pspline(t,s)   k := 0 ..50 $tspl_k := 7 + .2 \cdot k$

sspl := interp(cs,t,s,tspl)   Cubic spline through solar irrad.



Solar Irradiance vs. Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

S(arg) := interp(cs,t,s,arg)   t1 = 8.72   Start scenario

$heat := \int_{t1}^{t2} S(T)\, dT$ t2 = 13.92   Stop time

$heat = 4.075 \cdot 10^3$ W/m2 * hours

$aveheat := \dfrac{heat}{t2 - t1}$ aveheat = 783.737   W/m2

solar.mcd
2/10/93

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

$a := \mathrm{READPRN}(aug26)$

Start $t1 := 8.10$ Decimal time, EST

Stop $t2 := 12.35$ " "

$Na := \mathrm{length}\left[a^{\langle 0\rangle}\right]$

$j := 0 \,..\, Na - 1$

$Na = 12$

$s := a^{\langle 1\rangle}$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0\rangle} - .5$ t is vector of time points

$a =$

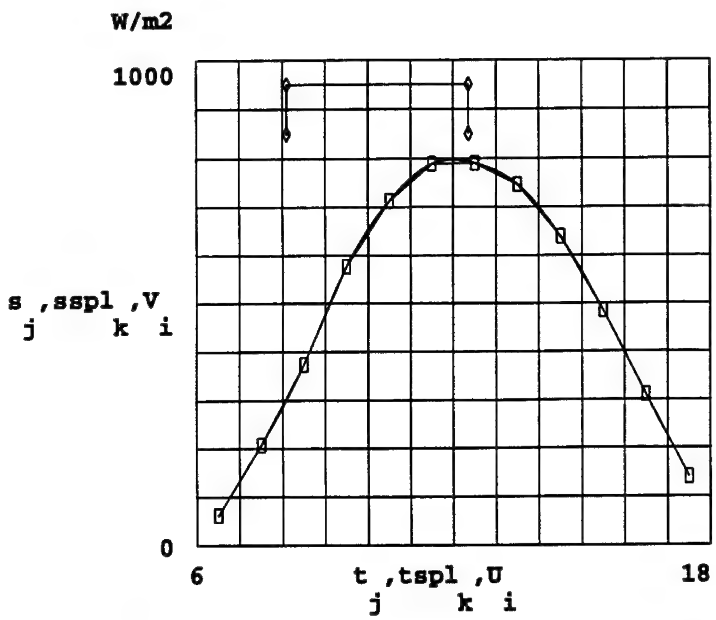
Time EST	Ave. W/m2 previous hour
7	62.3
8	207.8
9	374.7
10	576.9
11	713.2
12	789.4
13	790.5
14	746.5
15	638.5
16	485.1
17	311
18	140.6

$i := 0 \,..\, 3$

$$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix} \qquad U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$$

$cs := \mathrm{pspline}(t,s)$ $k := 0 \,..\, 50$ $tspl_k := 7 + .2 \cdot k$

$sspl := \mathrm{interp}(cs,t,s,tspl)$ Cubic spline through solar irrad.



Solar Irradiance vs. Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

$S(arg) := \mathrm{interp}(cs,t,s,arg)$

$t1 = 8.1$ Start scenario

$t2 = 12.35$ Stop time

$$heat := \int_{t1}^{t2} S(T)\, dT$$

$heat = 2.696 \cdot 10^{3}$ W/m2 * hours

$$aveheat := \frac{heat}{t2 - t1}$$

$aveheat = 634.464$ W/m2

CALCULATE AVERAGE INSOLATION DURING EXERCISE

Read in data for indicated date.

a := READPRN(aug28)

Start t1 := 8.08 Decimal time, EST

Stop t2 := 12.11 " "

$Na := \mathrm{length}\left[a^{\langle 0\rangle}\right]$

j := 0 ..Na - 1

Na = 12

$s := a^{\langle 1\rangle}$ s is vector of ave. solar irrad. for previous hour

$t := a^{\langle 0\rangle} - .5$ t is vector of time points

Time EST	Ave. W/m2 previous hour
7	85.5
8	155.8
9	441.5
10	607.1
11	667.6
12	797.6
13	642.7
14	522.1
15	278
16	308.3
17	82.9
18	7.7

(a = the matrix above)

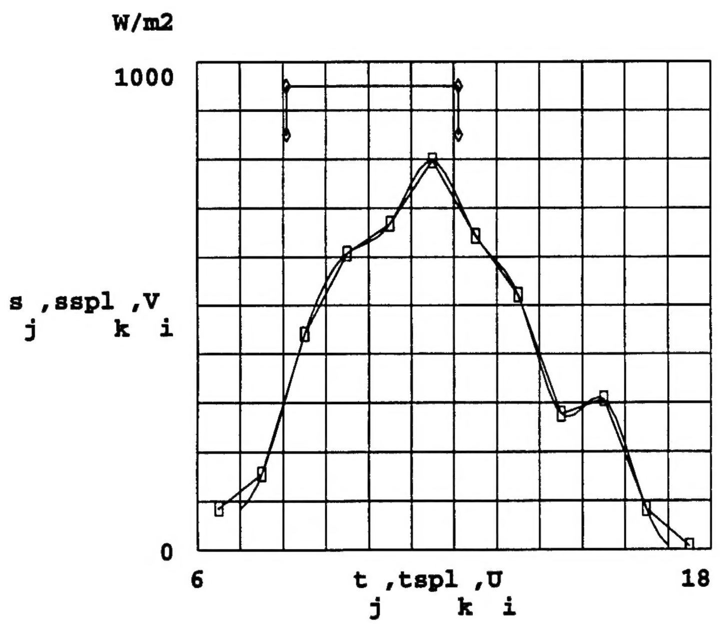
i := 0 ..3

$V := \begin{bmatrix} 850 \\ 950 \\ 950 \\ 850 \end{bmatrix}$

$U := \begin{bmatrix} t1 \\ t1 \\ t2 \\ t2 \end{bmatrix}$

cs := pspline(t,s) k := 0 ..50 $tspl_k := 7 + .2 \cdot k$

sspl := interp(cs,t,s,tspl) Cubic spline through solar irrad.



hours, EST

Solar Irradiance
vs.
Time

Exercise interval indicated

Both straight line and cubic spline interpolations.

S(arg) := interp(cs,t,s,arg) t1 = 8.08 Start scenario

$heat := \int_{t1}^{t2} S(T)\, dT$ t2 = 12.11 Stop time

$heat = 2.545 \cdot 10^3$ W/m2 * hours

$aveheat := \dfrac{heat}{t2 - t1}$ aveheat = 631.487 W/m2

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